Potential of renewable energies for the Finnish agriculture

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Abstract of the master's thesis

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Abstract

Renewable sources of energy are taking a central role in the new direction the current energy system is heading. Driven by goals of decarbonisation, the energy transition opens possibilities to local and distributed generation, and Finland has good opportunities to benefit from it. In that context, agriculture offers an appropriate niche for renewable energies, where the adoption of clean and local energy can positively affect farms and their wider society. Hence, the aim of this thesis is to estimate the potential of renewable energies in the context of Finnish agriculture. More specifically, this work focuses on the suitability of the solar photovoltaic energy in one of the most energy consuming agricultural activities, crop drying.

The potential of solar energy to cover the energy needs of crop drying is assessed in the Finnish context. A numerical analysis investigates solar photovoltaic energy with respect to electricity consumption in grain drying. This is done by simulating the solar PV production and the consumption of the dryer from a reference case, considering the use of battery storage and comparing the economic viability of different installed PV and battery storage capacities. The use of solar photovoltaic energy in combination with heat pumps is discussed in the context of the heating needs of crop drying, using a second real case as a reference.

The main conclusion is that solar PV can bring significant energetic and economic savings to the activity of crop drying, already with current conditions. In addition, the future promises yet better conditions for distributed generation, and further research and development in this area is essential for the decarbonisation of the energy system.

Keywords Agriculture, Solar photovoltaic, Energy consumption, Potential, Energy storage, Crop drying

Preface

This Master's thesis has been conducted as part of the Smart Energy Transition – project, funded by Strategic Research Council, Academy of Finland. In this regard, I would like to thank my main advisor Armi Temmes for the opportunity to engage in such an interesting project and for her ideas and guidance of the thesis. Together with Armi, I would like to thank others who made a comfortable working environment while I was working on the thesis, especially Allu Pyhälammi. In addition, I would like to thank my other advisor Jouni Juntunen, for the interesting course that led me here and for his advice during the thesis process.

I also want to thank my supervisor John Millar for his kind attitude, in addition to his supervision and advice for the thesis. My greetings also to Markku Välimäki from "Kasken tila" and to Petteri Kulmala from "Kustavin Agri" for sharing their knowledge, information and data, and showing me their facilities. Last, I would like to mention friends and people I have met in the "town square" and surroundings, who have encouraged me, and especially the ones who have been and are in the same situation with the "T". Cheers to all of you.

I have to admit that completing this thesis has not been the easiest thing for me; it has been a whole learning process in several ways. Among other reasons, the ambition at the beginning has occasionally turned into ambiguity or confusion in the struggle to remain within certain limits, while trying to swim in the ocean of the multidisciplinary perspective. This thesis has somehow tried to narrow distances between fields that often may be too far from each other, but fields that have much to share. Hopefully the recently achieved closer physical proximity will foster a more integrated approach in the future.

Otaniemi, 25.7.2019
Aitor Ossa Rissanen

Contents

Symbols, units and abbreviations

Symbols

€	Euro
i	Discount rate
n	Lifetime of system
t	Period in years
%	Percent
Q_h	Heat energy
W_e	Electric energy

Units

°	Degree
°C	Degree Celsius
GWh	Gigawatt hour
Ha	Hectare
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
kWp	Kilowatt peak
kWh_c	Kilowatt hours of capacity
MW	Megawatt
m^2	Square meters
TWh	Terawatt hour
W	Watt
Wh	Watt hour

Abbreviations

AMR	Automatic meter reader
COP	Coefficient of performance
HP	Heat pump
HTHP	High temperature heat pump
H_20	Water
PV	Photovoltaic
NPV	Net present value

1 INTRODUCTION

In the context of global warming and energy production based on fossil fuels, the current energy system is becoming obsolete and faces new challenges for the future. Promoting energy efficiency and increasing the use of renewable energy sources and other concepts, such as smart grids and demand response, will all take their part in decarbonizing the energy we consume. The energy transition is already bringing new possibilities to an energy sector that depends largely on fossil fuel imports and is centralised to a large extent, giving way to distributed, carbon-free and local energy production.

Finland, in this context, finds itself having to replace current energy production with generation that is more appropriate, but requires other ways to manage it. These new sources offer energy that emit no unwanted pollution, but they have certain spatial and temporal limitations that bring the need to find appropriate sites for the production as well as to appropriately handle imbalances. That is, the most important renewable energies, solar and wind, provide significant sources for the distributed energy generation, but their stochastic production brings new challenges in terms of the timing and quantities of produced energy. In other words, they produce energy depending on the availability of the source and not on the energy needs, thus temporal matters become essential in the energy regime. In that context, most of the renewable energy production systems need to be connected to the main electricity grid if no energy storage system is used. Nevertheless, technologies such as wind turbines or solar photovoltaic (PV) panels give a good opportunity to generate clean energy close to the place where it is consumed. Therefore, with the increase of renewable energy production, the energy system is becoming progressively more distributed.

Rural areas in Finland, as in many other countries, are usually far from the points where energy is produced, being the first sites to suffer energy shortages when problems occur. Furthermore, farms are in most cases places with vast areas, where lack of space is not the main worry, and usually their only source of energy are fossil fuels besides the electricity from the network. The electricity is used in several activities, such as crop and milk production, but also in the heating of agricultural production spaces or for operating machines. Taking into account that such energy uses have different consumption profiles as well as different energy needs, several possibilities appear for the distributed energy production in the context of agriculture.

The new direction of the energy regime brought largely by the renewable energy sources, together with the new possibilities in handling energy matters, give rural areas a good opportunity to actively take part in the decentralization and decarbonisation of the energy system. In addition, agriculture can benefit from the transformation of the energy system, not only by having local and more affordable energy for its own uses, but also by providing distributed and clean energy to the system.

Overview of the thesis

After the above introduction to the general context, the thesis continues in Section 1.1 by introducing the current situation of agriculture in Finland. Linking that with the main topic of the thesis, Section 1.2 explains the situation of renewable energies in the context of the Finnish agriculture. Once the main areas of this work are introduced, Chapter 2 carries out the literature overview about the energy consumption of agriculture in Finland covering the main agricultural activities. That chapter ends by concluding with the main points of the literature review, and narrows down the focus of the thesis to crop dry and solar photovoltaic energy, which forms the main part of the work.

Divided into three parts, Chapter 3 explains the main work of the thesis by defining the materials and methods used during the process. The first part, Section 3.1, describes the process of estimating the capacity of the solar photovoltaic energy to cover the energy needs of crop drying at a general country level. Consequently, Section 3.2 explains the process of the main analysis in the thesis. That is, this section addresses the suitability of solar photovoltaic energy in the electricity use of crop dryers, based on a real case. After that, Section 3.3 finalises the materials and methods chapter by covering the part corresponding to the potential of solar photovoltaics with regard to the heating needs of the grain drying, using a second real case as a reference.

Chapter 4 also is divided into three sections; it displays the results obtained in the thesis and discusses them. In the same way as the previous chapter, the first part is about the general numbers, the second section is about the solar PV in the electricity use of dryers and the last part is about the heating needs and the solar PV. Finally, Chapter 5 presents the conclusions of the thesis.

1.3 Agriculture in Finland

Agriculture is an essential sector in Finland. It is an important part of the Finnish economy, together with forestry and the food economy, to which is largely related. It is the main pillar for the food system of the country and provides a large variety of material and immaterial resources to the society. According to OECD, over 40 % of Finns live in rural areas, and approximately nine out of ten farms in the country are run by families, thus agriculture constitutes an important base for the living of a significant part of the Finnish society. In addition, 68 % of the exports are based on goods and resources that come from agriculture and 30 % of the Finnish enterprises are related to agriculture or are located in rural areas (LUKE 2016).

Despite the important role of agriculture, its development in the last decades shows a negative tendency. It is widely known that rural areas have been depopulating already for several decades in Finland, following the general global trend, and farms are no exception. That decrease cannot be perceived in the amount of agricultural products produced annually in Finland, but statistics about the number of farms, for example, show a clear decrease in agricultural units. From 59.483 farms counted in Finland in 2010, statistics show that 47.633 farms remained with some kind of agricultural activity in 2018 (LUKE 2019). That is, the number of active farms in the country is decreasing, but the total agricultural output is not decreasing, meaning that the average size of farms is constantly increasing. That indicates that the type or ownership of agricultural units is changing towards a more industrial form. In fact, statistics show that family- or private-owned farms are decreasing the most while the number of company-owned farms has increased in recent years (LUKE 2019).

From the point of view of energy security, farms are often in vulnerable positions in relation to the energy grid and the available energy. Being far from urban and other constructed areas, they usually depend on long radial electricity networks that go through forests and other complicated areas making them vulnerable to failures and accidents. Thus, farms are usually the first to suffer power outages when storms or other situations of risk occur, and are the last to recover connection to the grid. Hence, many of the farms have backup power sources in order to maintain their critical products or activities in such situations, and usually those alternative power supplies are diesel generators.

Nevertheless, fossil fuels are not only used in farms for backup power generation, and in fact, agricultural activities depend largely on fuel for uses such as operating machines or heat production. According to statistics from 2016, all fuel consumed that year in the Finnish agriculture was carbon-based, and fossil fuels constituted 36 % of it (LUKE 2018a). In conclusion, agricultural activities depend on the energy that is brought to the place through the electricity networks or by other ways in the form of fuel, and the only energy that may be local are carbon-based biofuels.

As mentioned above, the availability of electricity is not fully secure and it depends on climatic and other factors difficult or even impossible to predict. Biofuels can be produced locally or within reasonable distances, but fossil fuels are imported not only to farms but also to the country. That is, fossil fuels are imported from other countries, thus Finland depends on external factors when it comes to the supply of the energy, meaning that there is little control on the price or the availability of the fuel. Considering the current global situation of geopolitics and environmental problems, the matter of energy security is raising concern and farms are in a weak position due to their dependency on energy availability as well as price.

In that context, renewable energy sources bring new possibilities for producing emission-free energy locally and with no cost of production. In fact, although the energy consumption of agriculture constitutes 3 % of the total energy consumed in Finland, the sector produces around 12 % of the greenhouse gas emissions in the country, and it is the third largest emitter after the energy and transport sectors (OSF 2019). Therefore, decarbonisation has a significant weight in the energy production as well as its consumption in agriculture, a decarbonisation that will occur largely through the adoption of renewable energies.

Besides the already mentioned biofuels, all other sources of renewable energies produce carbon-free energy without additional costs other than the investment, and maintenance in some cases. Among them, solar and wind energy are most commonly used and are good examples of producing free energy with no emissions. However, they have certain limitations that hinder their adoption and use against current traditional energy sources, such as temporal limitations or technical as well as economic feasibility. In conclusion, there is a need for further development and adoption of renewable energies in a general level. The agricultural sector, besides being included in that general context, offers good possibilities for the decarbonisation of the energy system through decentralized and emissions-free energy production.

1.4 Renewable energies in the Finnish agriculture

Heretofore, biomass is certainly the source of energy that is most used in the agricultural sector among the renewable sources. As already mentioned, biofuels such as wood, pellets and wood chips are largely consumed in farms and they constitute around half of the total energy consumed in agricultural activities (LUKE 2018a). Besides that, the contribution of renewable energies is marginal in the Finnish context, meaning that very little emissions-free energy is produced locally in comparison with the total energy consumption.

Among the renewable energies used in agriculture besides bioenergy, virtually all are used to produce electricity and have the sun as the source of energy. Solar photovoltaic predominates in the area of emissions-free and distributed energy production in agriculture, and more installations are being adopted and used all around Finland. In most of the cases, solar photovoltaic units have been installed in farms with milk production, where the solar energy production offer good potential in reducing significant amounts of electricity consumption (Posio 2014, Niemi 2017).

In fact, farms in general offer good conditions for the energy production from renewable sources due to the availability of appropriate spaces. They usually have several buildings close to each other, such as houses, barns or garages providing large rooftop areas, for example, to install solar panels. Farms often also have open spaces around them that are not used for any purposes, where windmills or biomass production units can fit without major problems. In addition to rooftop areas, the buildings also tend to have significant indoor spaces that can be used for several different purposes, in this case for inverters, batteries or other systems required for renewable energy production.

Therefore, solar potential as well as the potential of wind energy in other agricultural activities are raising interest, although there is little research done in the area (Pöyry 2017, Korri 2019, Rantala et al. 2016, Arffman 2013, Pulkkinen 2017). In the region of Etelä-Pohjanmaa ―Southern Ostrobothnia in English―, for example, it is estimated that using rooftop areas of the region, up to 80 % of the yearly domestic and agricultural electricity consumption could be covered with solar power in terms of amounts of energy (Haapaniemi et al. 2016).

Thus, there is potential for renewable energies in agriculture, but there is still a need to analyse further and to build knowledge about the different possibilities of adopting these new energy production systems. In that way, and considering the goals of increasing the share of renewable energies in Finland, the supports for investments for agriculture are important to mention. On the one hand, supports that cover between 10 and 30 % of the investments on renewable energy production systems can be obtained, and the amount of support varies depending on the source of energy used or the size of the system. On the other hand, supports of up to 40 % are available specifically for investments made in agriculture, including energy production systems that are based on renewable energy sources (Motiva 2015).

The potential of renewable energies in agriculture, however, is not only in energetic terms, and it can provide more than just energy to farms. On the global as well as the Finnish context of the decarbonisation of energy and the transformation of the traditional energy system, farms can provide distributed and emissions-free energy and thus contribute to the new direction. Further, they also can benefit from it by creating new business models or farm structures that could support agricultural activities. In relation to energy prices and availability of resources, the production via renewable energy technologies can provide, in large amounts, local and virtually free energy, ensuring better energy security and simultaneously supporting rural areas in decline. That, in combination with good spatial conditions and supports for the investments, can put agriculture in the front line of the energy transition.

In that context, this thesis aims to analyse the potential of renewable energy sources for agriculture in Finland. It intends to contribute to the knowledge base about the challenges of the current energy system and their solutions. By measuring and evaluating renewable sources, the thesis contemplates different possibilities to improve the current situation of energy, and evaluates their capacity for doing it from the perspective of agriculture. For that, it is first important to know with more detail what the current situation is, that is, what kind of energy is used and how much is used in agriculture. Therefore, the next chapter analyses the energy needs of farms, reviewing the literature about the topic and focusing on temporal and quantitative characteristics.

2 ENERGY CONSUMPTION IN THE FINNISH AGRICULTURE – A LITERATURE REVIEW

The renewable energies offer a wide variety of options to produce energy locally for agriculture, and different sources can supply energy to different agricultural energy uses. In order to know what can be used and how, the first step is to know which are the needs. That is, energy consumption in agriculture must be known if the best outcome is meant to get from renewable energy production. Thus, this chapter undertakes a literature overview about the different uses of the energy in the context of the Finnish agriculture, focusing on the direct energy.

Direct energy is what is directly consumed in the farm as electricity or fuel, and takes a large part of the main activities in the production. Indirect energy consumption, on the other side, constitutes all other sources that are used in the production, but are brought in other forms to the farm so their energy value is based on their own production process. The fodder for animals or the fertilizers for crops, for example, are counted as indirect energy consumption while the oil for heating or the electricity from the network are taken as direct energy. As this study is centred on the local energy production with renewable energies, direct energy is the matter that best defines the energy needs in this case.

When looking at the different energy consumptions of the agricultural processes, special attention is put to the temporal and quantitative dimensions. That is, the most relevant part of the consumption is the amount and the timing of the energy. Therefore, the energy needs can be analysed with more detail, better information can be obtained from it and a more complete picture of the possibilities will be possible to create.

On average, the total energy consumption in Finland has been 380 TWh in the last decade, from which around 3 % has been consumed by the agricultural sector. Close to a fifth part of the energy consumed in agriculture is consumed as electricity and the rest is consumed as fuel. In 2016, for example, the agricultural sector consumed 9.105 GWh of fuel, including biofuels, while the electricity consumption was 1.741 GWh (LUKE 2018a).

From the total agricultural energy consumption, agricultural machines consume 33 %, livestock production 29 % and grain dryers as well as residential buildings have the same share of 19 %. When it comes to the fuel use, agricultural machines such as tractors, combine harvesters and sowing machines consume the most with a share of 42 % of the total fuel use, while space heating shares 36 % and crop dryers 22 %. In relation to the electricity use, in livestock production the share of electricity is about 20-30 %, the piggeries have the greatest electricity share while broiler hatcheries have a 12 % and crop production has an 8 %. (Työ- ja elinkeinoministeriö, 2011)

2.1 Crop production

Grain production has an important role in the Finnish agriculture and it is the most common agricultural practice in the country. It is the second largest energy consumer by sectors after milk production, and provides a significant source of food for humans as well as for the animals in the livestock production.

The process of crop production involves different stages around the year, field works such as ploughing, sowing and threshing, and the grain is usually processed in order to conserve for longer periods. Hot air drying is the most common method to conserve crops over seasons, and other methods such as airtight storage, acid preservation or grain crimping are not very much used (Jokiniemi 2016). Ambient air dryers are secondly most used, even if their presence has decreased in the last decades. Besides, the use of storage and drying silos has increased as pre-driers of the grain, for the later proper drying of it. In the case of hot air dryers, temperatures between 60 and 80 °C are usually needed to dry the grain until the desired moisture level, but higher temperatures such as 100 °C may be needed depending on the grain type and the end use of it. Due to the Finnish weather conditions and the relatively reduced sizes of the farms the production of crops is not constant over the months and the years, meaning that the energy consumption of the process is neither continuous and that it can vary depending of the weather, and few are the dryers in Finland that work continuously. (Viita 2013)

The high variability of the energy needed to dry crops complicates to give standard values of energy consumption levels. Usually, the energy consumption of drying is expressed in relation to the amount of water evaporated, but it also can be expressed in relation to the amount of dried crop. As the moisture level of harvested crops varies among different grains and different periods, values of the energy consumption that are based on the amount of dried crop also vary significantly. Therefore, expressing the energy consumption level based on the amount of evaporated water is more accurate. However, the production of crops is measured as the weight of dried grain, and the amount of evaporated water is not used in such cases, thus giving values of the energy consumption based on the amount of dried crop may be more practical in some cases.

Considering only direct energy consumption, grain drying is the most energy demanding process (Vainio 2017). According to Ahokas (2013a), the process of grain drying consumes around 0,15 l of fuel or its equivalent of 1,4 kWh per kilogram of evaporated water, usually the grain having around 20 % of moisture before and 14 % after the drying. Another report concluded that the hot air dryers consume between 1,4 and 2,0 kWh per kilogram of evaporated water (Hautala et al. 2013). Regarding the processed amount of crop, the average energy used to dry 1.000 kg of grain is estimated at about 150 kWh (Hautala et al. 2013).

When it comes to the electric energy use, the electricity consumption in the process is estimated at about 10 % of the fuel consumption, and it is used mainly by the fans, feeders and other electrical machines involved in the process (Ahokas 2013a). Regarding the size of dryers, it is defined by their nominal power and it varies a lot depending on what are the needs as well as on the temperature and airflow that are needed in the process. Figure 1 shows the relation between the nominal power of the dryer, the temperature and airflow.

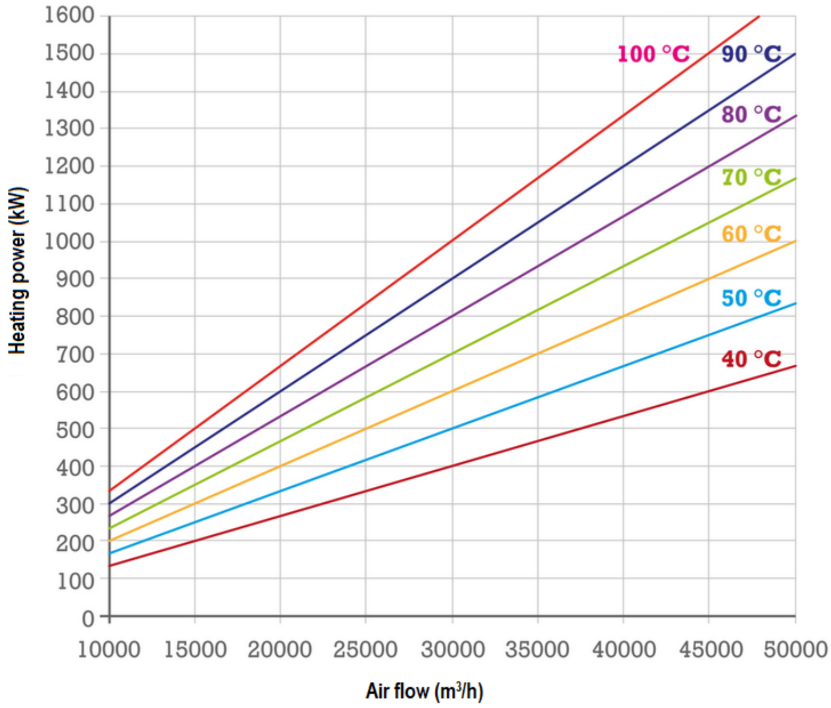

Figure 1: The power needed in the dyer depends on the air mass and the drying temperature (Ahokas and Jokiniemi)

A study carried out between 2005 and 2006 in the Swedish agriculture, where weather conditions are similar to the Finnish ones, got results of some dryers where electricity consumption per 1000 kg of dried crop was between 4,2 and 9,1 kWh, noting that the values changed about 30 % from a year to another due to the weather conditions. In the case of the ambient air dryers, values of 0,27-1,0 kWh/kg H_2O and 13,5-50 kWh/ton were obtained. (Hörndahl 2008).

In the case of the ambient air dryers in Finland, where energy is used only as electricity by the drying air fans, the consumption have been estimated at around 0,3 and 0,4 kWh per evaporated water kilogram. With such technology, the period when the grain can be dried is more limited, and considering outside relative humidity and temperature, according to Jokiniemi, drying to the wanted moisture content of 14 % with no extra heat is only possible in average from April to September, and for only few hours per day. (Jokiniemi 2016)

For the Finnish weather conditions, where crop is harvested in the end of summer, Ahokas and Jokiniemi estimated that threshing can be carried out, on average, on 20 days between the middle of August and the end of September. Two batches per day was assumed to be the general norm for the hot air dryers, but it can vary depending on the grain type, temperature, moisture and other factors (Ahokas and Jokiniemi). In a simulation where several batches of barley were dried, for example, it was calculated that the drying of 11,5 tons with temperatures of nearly 80 °C required between 3 and 5 hours (Viita 2013). Being aware of the different factors affecting the drying time, other studies have shown that dryers may need between 2 and 20 hours to dry a batch, with an average value of 7 hours (Suomi et al. 2003). For ambient air dryers, in the other hand, as no external heat is used, the time of drying extends to several days or even weeks.

2.2 Livestock production

The production of animals consumes large amounts of energy and farms that dedicate to such activities are the most heavy energy consumers in the agriculture. In many of the cases the fodder for animals is produced on the same farm, thus crop production also is involved in the livestock production when talking about total energy consumption. Considering that only direct energy consumption is taken into account in this study, the grain drying is the most relevant part as it is the largest direct energy consumer for the fodder production. Therefore, it is assumed that the part of the fodder production is covered above in the section of crop production.

Energy consumption values may change a lot from a farm to another even the production output is the same, and many factors are the cause of such variations. Insulation of the buildings, lighting times, use of ventilation or different habits can cause the consumption to be higher or lower. As the milk, pork and broiler chicken productions have the highest energy needs among the livestock production, the literature review will only consider them. The beef production, for example, has similar energetic needs than the milk production, but has less need for electricity due to the absence of machines such as milking systems. Therefore, it is less interesting for this study, and in addition, it could be assumed that their needs are represented by the review about the milk production.

Cows usually need little or no heating when they are in the cow houses due to their capacity of resisting relatively cold temperatures and to the buildings that are usually sufficiently well insulated. Pigs and chickens, on the other hand, do not tolerate cold temperatures that well, and their high energy consumption is caused by the need for extra heating, which is mostly produced with fuels. In the case of the electricity, cow houses have higher consumption as the milking process requires more electric energy than the other animal productions cases. Milking consumes the most electric energy in livestock production, but other uses can also be large depending on the needs. Other uses are, for example, ventilation and lighting of the spaces, removal of the manure, water pumps and feeders. Besides electricity, the rest of the direct energy is coming from fuels that are used in feeder or manure removal machines as well as in space and water heaters. (Ahokas et al. 2014)

2.2.1 Dairy farms

Milk production, or dairy farming, is the most energy consuming type of farm, and in 2010 it used 30 % of the direct energy in the Finnish agriculture. Its main use of energy corresponds to the milking process, involving milking, milk cooling and the heating of cleaning water in electric boilers. Space heating is not usually needed on dairy farms as cows can usually tolerate cold weather, but a minimum temperature has to be ensured in order to avoid freezing of the water or the manure (Ahokas et al. 2014). Academic research made in Finland reported that per year and per cow, electric energy consumption was between 622 and 1178 kWh and heating between 267 and 328 kWh. Feeding and milking were reported as the largest electricity consumers, and heating of the cleaning water as the main consumer of thermal energy (Posio 2010).

According to a study carried out in Southern Finland where three dairy farms were observed, the milking process consumed electricity between 37 and 62 Wh per kilogram of milk, and it entailed about 48 % of the total electricity consumption of one of the farms. It has to be noted that the amount of heated water for cleaning the milking system hardly changed with the amount of milk produced or the numbers of animals, while the energy required for cooling the milk was proportional to the milk production. The electricity consumption from milking was 9,1-29,3 Wh per kilogram of milk, milk cooling gave results of 18,5-24,9 Wh and the water heating was 9,7-22,8 Wh. Although the milking process was roughly the same independent of the season, the total electricity consumption was higher in winter than in summer due to other consumptions such as lighting and heating of spaces. Figure 2 shows measurements from one of the farms. (Rajaniemi et al. 2017)

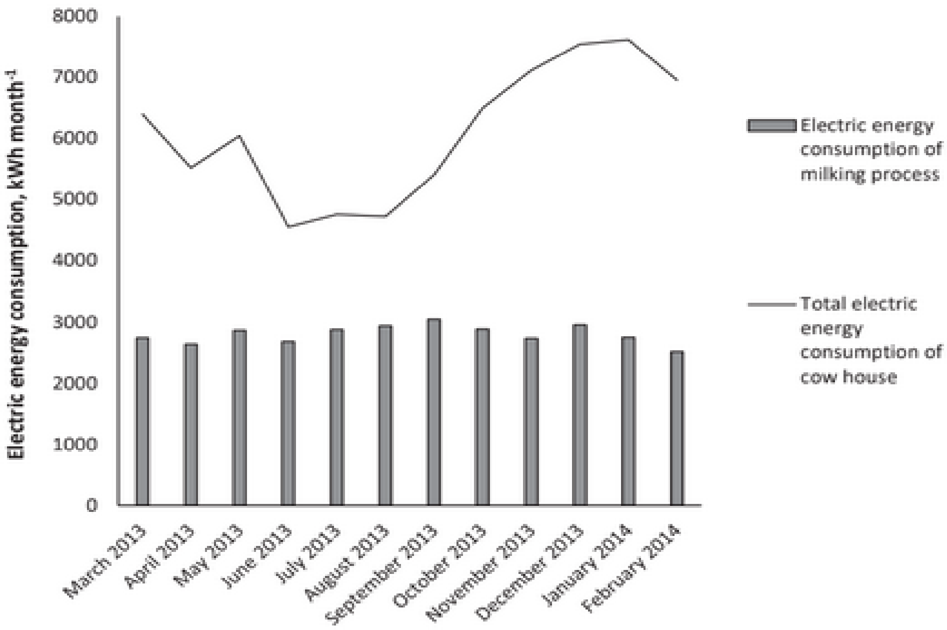

Figure 2: Monthly electric energy consumption of the cow house and the milking process of a farm (Rajaniemi et al. 2017)

According to Ahokas et al. (2014), based in several studies carried out mainly in Sweden, the milking process consumed energy between 0,017 and 0,064 kWh per produced kilogram of milk. Seasonal differences were seen in measurements from an Estonian dairy barn, where electricity consumption in winter was higher mainly due to the illumination and ventilation needs, as it is darker outside and the air for ventilation may be heated a bit. Table 1 shows different consumption values for each task of the milking process based on different studies, and Figure 3 represents the monthly consumption of an Estonian cowshed for a year and the division of each task.

Table 1: Energy consumption in milk production (after Ahokas et al. 2014.)

Task	Wh/kg milk
Lighting	12-27
Milking and cooling	17-64
Manure removal	2-14
Ventilation	0-30
Feeding	2-72
Miscellaneous	8-38

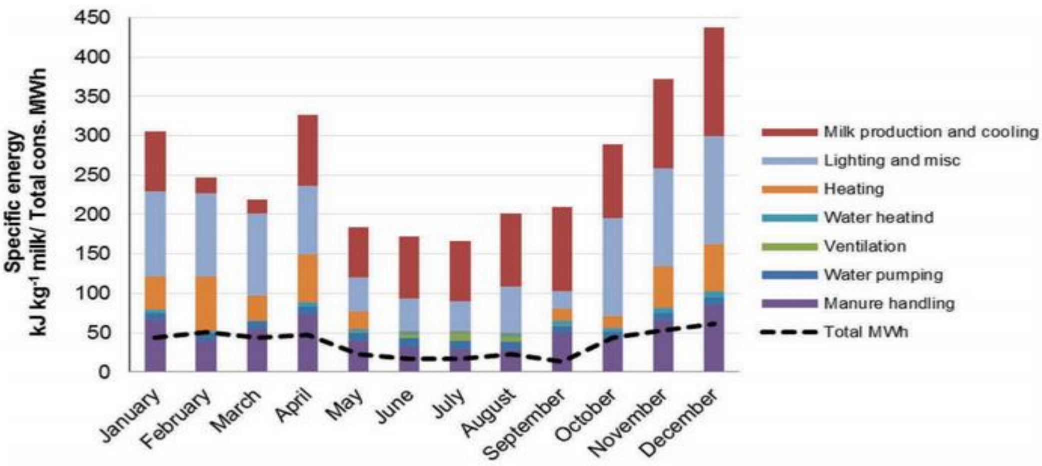

Figure 3: Example of an Estonian cowshed with 596 cows in 2011 (Ahokas et al. 2014)

When it comes to the power needs of dairy farms, Torsten Hörndahl reports that the milking and the fodder systems show high loads during the day while power needs at late evenings and nights are quite low. In addition, 50 % or more power was used for no more than 10-25 % of the week. Figures 4 and 5 represent measurements from two different farms in Southern Sweden. (Hörndahl, T. 2008)

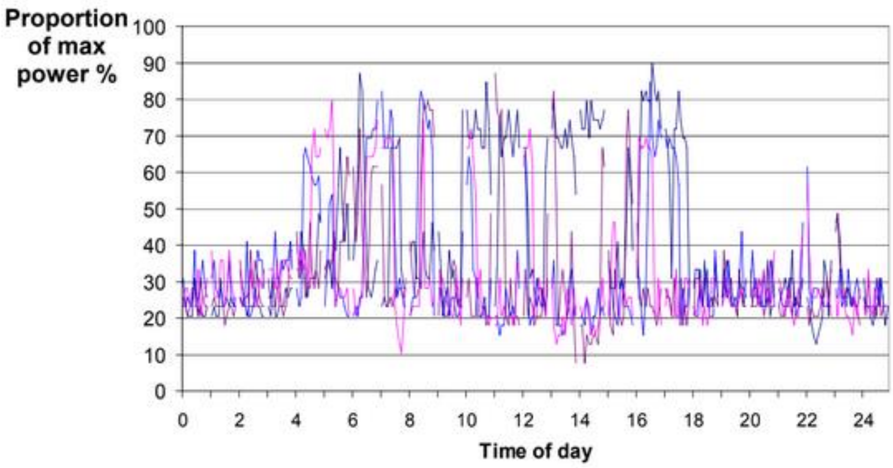

Figure 4: Average power of a farm over four weeks (Hörndahl 2008)

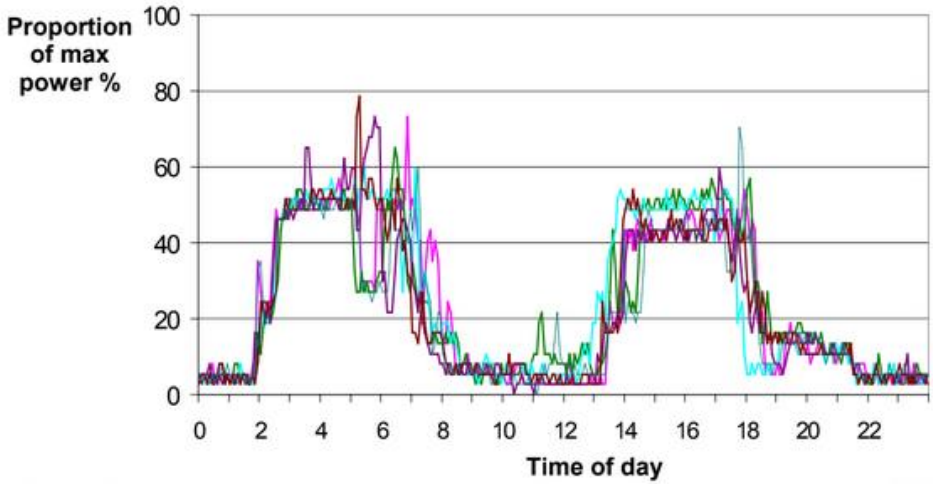

Figure 5: Average power of a farm over six days in April (Hörndahl)

2.2.2 Pig farms

In Finnish pork production farms, most of the direct energy is usually used for heating and ventilation of the spaces. Heating is needed especially in the cold season as the pigs do not tolerate very cold climates, and the ventilation is needed all around the year because the animals produce gases that must be removed in order to ensure proper air quality (Ahokas et al. 2014). Besides, other consumptions happen for water pumping, feeding, lighting, cleaning and other marginal tasks. (Vainio 2017)

However, the type of piggery determines the needs of the direct energy in the farms, as piglet production has different needs compared to the finishing pig production. According to Ahokas et al. (2014), a study carried out in Sweden estimated that in the piglet production heating consumed 51 % of the direct energy while ventilation used 19 %, lighting 14 % and feeding 10 %. In the case of the finishing pigs, heating consumed only 14 % of the direct energy, while 42 % was used for ventilation, 6 % for lighting and 33 % for feeding.

Table 2 shows the division of energy uses of the piglet production as well as the total direct energy consumption. The ventilation was assumed to be operating throughout the year, thus 8760 hours, while lighting was established to be 10 hours per day. It has to be noted that the value for heating includes the heat lamps that are powered with electricity, estimated at 212 kWh/sow/year. (Posio 2010)

Table 2: Energy consumption in piglet production, per sow and per year (after Posio 2010)

Task	**kWh/sow/year**
Lighting	78
Manure removal	3-8
Ventilation	30
Water pumping	4-10
Feeding	13-90
Hot water	83
Heating	358-535
Total of heating and electricity	569-833

Consumption values for the finishing pigs are shown in Table 3. The data is per pig and per year, considering annually two batches. In this case, the lighting was estimated at eight hours per day and for a part of the year, as no need for artificial light is needed between May and August. Besides, it was calculated that the animals stay on the farm for 315 days, thus the yearly need for lighting was estimated at 1.680 hours. The ventilation and the water pump work only when the pigs are in the piggery, so 7.560 hours was the estimated time for both uses. For finishing pigs, heating is needed only when the outside temperature decreases to below a certain level, and the days when heating is needed were calculated to be between 9 and 21, depending on the region. (Posio 2010)

Table 3: Energy consumption in finishing pig production, per pig and per year (after Posio 2010)

Task	**kWh/pig/year**
Lighting	5
Manure removal	0,5-5
Ventilation	8
Water pumping	0,5-1,2
Feeding	2
Hot water	16
Heating	28-170
Total of heating and electricity	61-209

2.2.3 Broiler chicken farms

In Finland, there are about 190 broiler chicken production farms, most of them in the South-Western regions. The hatcheries use the all-in all-out system to grow the chickens, meaning that 6 to 8 batches of around six weeks are grown annually, with a few weeks in between for cleaning and preparing the hatchery for the next batch. (Ahokas 2013b)

Heating is the most direct energy consuming task in broiler hatcheries, 1,3-1,5 kWh per kilogram of carcass weight according to several studies (Rajaniemi and Ahokas 2015, Ahokas 2013b and Vainio 2017). Hatcheries are heated all around the year but, as Figure 6 represents, the need for heating is larger in winter than in summer because the chickens do not tolerate very cold temperatures. Thus, heating needs may be very large during the coldest days, while it may not be necessary in the hottest days. Most of the heating is used at the beginning of the batch as the animals require a certain temperature in the first days, but then the temperature is decreased stepwise during the rearing period and the lowest need for heating is in the end (Ahokas et al. 2014).

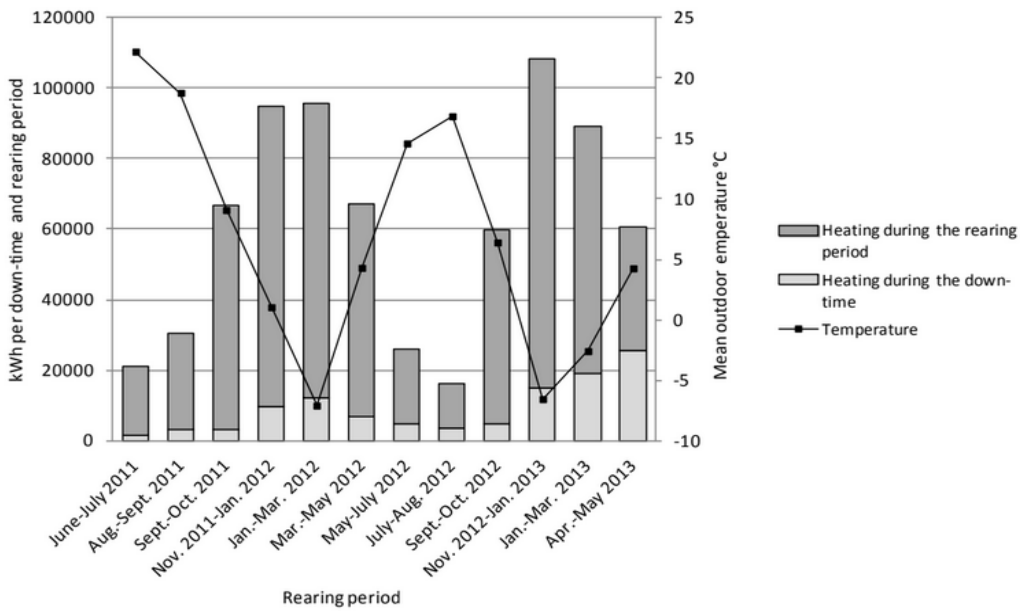

Figure 6: Energy consumption of heating for 12 flocks (Rajaniemi and Ahokas 2015)

Electricity is used mainly for ventilation and illumination but also for feeding and other marginal uses, and significant differences exist depending on the season as well as the stage of the growing. According to Rajaniemi and Ahokas (2015), the average use of electricity per kilogram of carcass is 0,08 kWh. When it comes to a whole batch, Hörndahl (2008) calculated that the electricity consumption of a batch of 100.000 animals was 3.340 kWh.

During the summer and warm days is when is used more electric energy, as the higher temperatures increase the need for ventilation. This can be observed in Figure 7, which represents the daily electricity consumption of a broiler house in Southern Finland. The graph also shows a clear increase of the electricity consumption during each flock. The rise is caused by the increasing need for ventilation that is required as the birds grow in weight and size (Rajaniemi and Ahokas 2015). Besides, two consumption peaks happen on each batch, where the second one is because of the increased need of ventilation. The first peak is due to the lighting needs of the chicks for the first days in the hatchery. After two or three days, the illumination is decreased and maintained almost constant during the whole flock, as Figure 8 shows, being the average consumption of lighting 0,01 kWh per kilogram of carcass weight. (Ahokas et al. 2014).

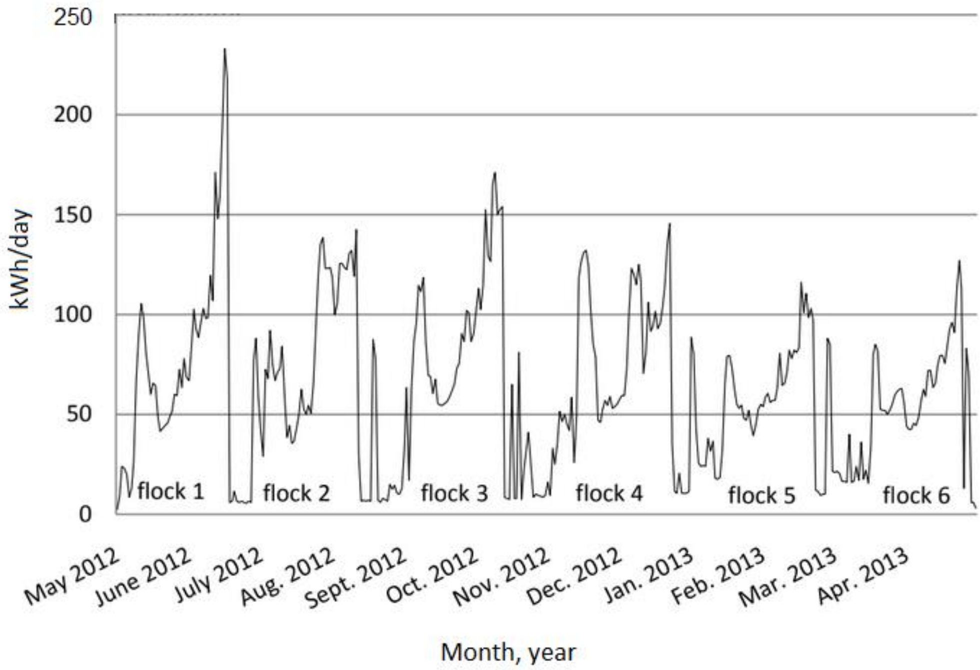

Figure 7: Electric energy consumption of a broiler house for a year (Rajaniemi and Ahokas 2015)

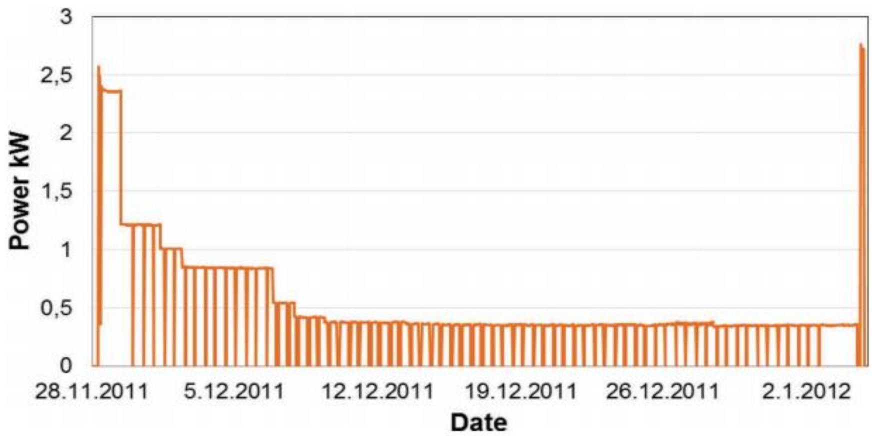

Figure 8: Power used in lighting a broiler house for a flock (Rajaniemi and Ahokas 2015)

Figure 9 compares the electricity and heat consumptions on each of the chicken flocks of a Finnish broiler house, showing a clear increase of the heating in winter and a higher electricity use in summer. (Rajaniemi and Ahokas 2015)

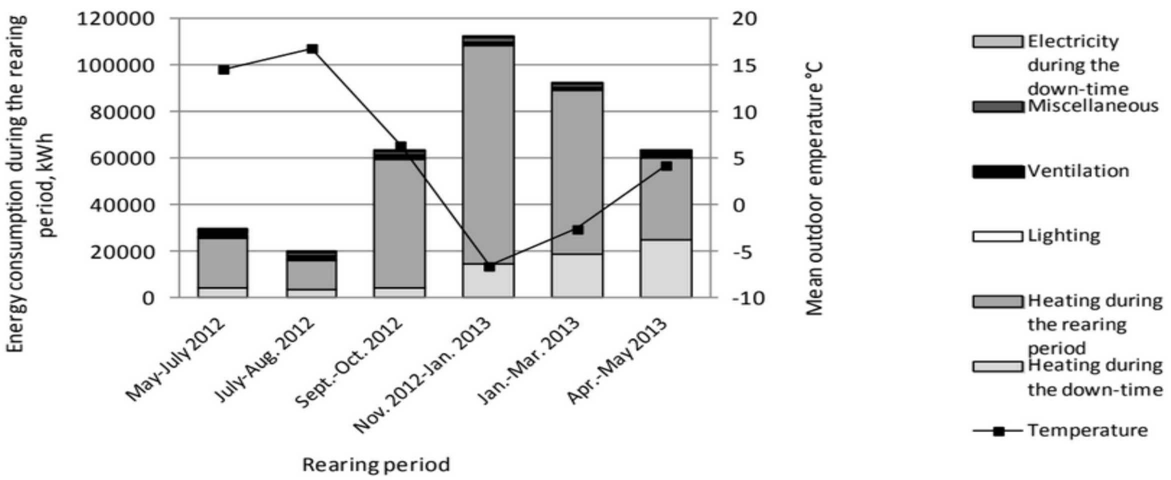

Figure 9: Heating and electricity consumption per batch for a year
(Rajaniemi and Ahokas 2015)

2.3 Concluding remarks from the literature review

The literature review has shown that the production of milk consumes more energy than any other agricultural activity in Finland. Space heating, an important energy need in this Nordic country, does not take centrality in the energy use of the dairy farms, while other needs such as ventilation, lighting and milk cooling take more importance. Especially the latter one, together with other tasks involved in the milking process, constitutes the most significant energy consumption of the milk production. Therefore, those processes make the milking to be a relatively constant energy consumer throughout the year, being it mainly based on the electricity consumption and having little dependency of heating. However, seasonal factors usually cause higher energy needs in wintertime due to the lighting, ventilation and some of the heating.

After the milk production, crop production is the second agricultural sector that consumes most energy, although it is the most practiced activity in the country. Unlike dairy farms, the energy consumption profile of these farms has two clearly different periods, as the largest part of the energy is consumed for drying crops at the end of the summer. The type of the energy needed also is different, and the heat consumption is, in many cases, much higher than the electricity consumption although the latter one is considerably high. A significant consumption also comes from the use of the agricultural machines employed for the field works at different periods of the year. However, the energy used for drying crops is more relevant in this case due to its temporal characteristics, but primarily because of the type of energy involved. Nearly all energy is consumed in a relatively short period, normally from the middle of August to the middle-end of September, and both electricity and heat are used simultaneously.

In the case of both pig and broiler chicken farms, heating is what consumes most energy. The consumption in summer may also be high due to mainly ventilation needs, but in cold and dark seasons significantly more energy is required as certain levels of illumination and temperature must be ensured. Therefore, the largest energy consumption of pigs and broiler chickens is concentrated in winter months.

Comparing the agricultural activities reviewed above, crop and milk production show the most interesting characteristics for this study that aims to analyse the possibilities of the Finnish agriculture to be benefited with the incoming renewable energies. One obvious reason is that those two are the most common agricultural activities in the country as well as the ones that most energy consume. Regarding to the main production sectors of the Finnish farms, 32 % are mainly dedicated to the grain production while 13 % produce milk as their main outcome. Besides, it is significant that 70 % of the farms are dedicated, mainly or partly, to the production of cereals (LUKE 2018b, LUKE 2018c). In consequence, the potential of crops and milk production is higher than other production types for replacing the traditional energy sources and for decreasing the carbon emissions linked to the energy production.

The other reason why dairy and crop production farms are interesting is their energy consumption profiles, not because of their similarities but rather because of their different characteristics of the energy consumption. In crop production, as stated before, relatively low levels of energy are consumed throughout the year, but large amounts are needed for a short period at the end of the summer due to the intensive energy needs of crop drying. The production of milk, on the other hand, does not have such seasonal variations and its energy consumption profile shows more uniformity than other agricultural activities. That is, in a large part, due to its main energy consumer, the milking process, that consumes almost the same amount of energy regardless of the time of the year.

As seen in the introduction, some work has been done about the solar photovoltaic energy in the context of the milk production (Posio 2014, Niemi 2017). When it comes to the grain production, literature can be found about using the energy from the sun as a source for drying the grain (Daghigh et al. 2010), but it has been limited to grain drying technologies that are relatively marginal in Finland, mainly the ambient air drying. This technology is used in the country by some farmers and crops producers, but due to its technical limitations it is not as common as the hot air dryer, predominant technology for crop drying in Finland. The hot air drying, although being the main method to dry crops, has not attracted much attention of researchers, and studies that cover this topic have focused on the efficiency of the process. Hence, from now on this thesis focuses on the agricultural activity of crop drying.

Crop drying further

It has been already stated that crop production is the most common agricultural activity in Finland, as well as the second largest energy consumer after the milk production. The grain is not produced only for a unique specific purpose and it has several different uses; it can have industrial purposes, for example, or it can be used as fodder as well as in the food chain. Due to its use as fodder, many are the farms in Finland that produce their own grain to feed the animals, thus the cereals are an important part of the livestock production. Besides its importance as a source of nutrition for the animals, the grain production has a large impact on the energy consumption of the farms that produce animal-based products, entailing a crucial sector in the energy use of the Finnish agriculture.

The use of crops in the human diet has increased over the last few years; especially the statistics of oat consumption show a clear growing tendency (LUKE 2019). The tendency is expected to keep growing as the plant-based diet is taking more centrality in the human nutrition, meaning that more crops will be needed in the future (Vainio et al. 2018). The animal-based diet may decrease due to environmental reasons and alimentary choices of the people, entailing that less cereal would be used for fodder. Nevertheless, the reduced animal products would have to be replaced partly by plant-based products. The latter ones would be crops, largely, hence an increase of the grain production can be expected in the close future.

As mentioned before, this thesis will only consider the energy consumed in the drying process of crop production. Crop dryings has been chosen because it entails the largest energy use of crop production, and also because temporal and spatial characteristics of this activity are more interesting. Virtually all the rest of the energy is used for field works as fuel for the agricultural machinery, and it is consumed unevenly from the spring until the end of the summer. The energy use in the agricultural machinery also is an interesting topic to research, and it has a big potential to reduce the use of fossil fuels in agriculture. However, its characteristics are out of the scope of this research, and another whole thesis would be required in order to address the topic.

About temporal features of crop drying, as mentioned earlier, farmers dry crops in the end of the summer between mid-August and the end of September, but the weather can cause variations prolonging or shortening the period. The solar radiation offers a significant amount of energy at that time of the year, although it is not its optimal season, and the performance may be even better than in hot days of the summer due to the appropriate temperature. When it comes to the spatial features, the grain is dried in drying units that are static and do not move unlike the agricultural machinery. Besides, they are located usually close to other buildings and structures of the farms, and usually have large available spaces close to them. Those spaces could provide good sites for other installations, for instance rooftop areas for solar panels.

Therefore, the perspective of the energy production also narrows and focuses on the solar photovoltaic. One main reason for that lays on the temporal adequacy mentioned above, as the solar energy in Finland is concentrated in the summer. Similarly, the timing of crop production is centred on the summer and drying occurs in the end part of the season, where the availability of solar energy is yet significant. That is, one of the most important agricultural activities and one of the most important renewable energy sources have similar seasonal timings, thus meaningful potential must exist.

The other main reason is that the solar photovoltaic technology, besides currently being well developed, promises a good future. The use of the solar PV energy has significantly increased in the last few years and it is broadly extended in the world as well as in Finland. With this tendency, its accessibility is constantly improving and prices of the technology are expected to decrease even more. Furthermore, the spatial accessibility of PV power is one of the best among the renewable energy sources as nearly every roof or other similar surface can be used for its adoption. In addition, the relative simplicity of this technology gives solar energy a good prestige. On the one hand, its installation is less complicated than many other energy production systems as the technology and the installation process are relatively simple compared to others. On the other hand, the easy accessibility of the data about the solar resource facilitates to predict the photovoltaic production for many years. Hence, the solar photovoltaic energy is the appropriate renewable energy for this thesis.

3 SOLAR ENERGY AND CROP DRYING

Divided into three parts, this chapter describes the material and the main methods used in this work, explaining the process that has led to the results and conclusions of this thesis. The first part, Section 3.1, estimates the potential of solar photovoltaic energy in the general level of crop drying in Finland. There, the annual energy consumption for drying crops is compared with the estimated production of the solar PV in agriculture.

The two next sections analyse the suitability of solar energy in the process of crop drying from two different perspectives, using two real cases as the reference. The first one of them, Section 3.2, analyses the suitability of solar PV energy from the perspective of the electricity use in crop drying, and is based on one of the reference cases. That is, the electric energy consumption of a dryer is compared with the potential production of the solar photovoltaic energy on the site. Section 3.3, based on the second reference case, focuses on the heating energy of crop drying and speculates about different possibilities solar energy could bring to this agricultural activity.

3.1 Crop drying and solar energy in Finland

3.1.1 Energy used for crop drying in Finland

Little information is provided about the exact numbers of the energy consumed in the process of crop drying in Finland. As the literature review has shown, no value of the energy consumed in the process can be considered as universal, and the information is usually given as a range that represent the usual energy consumption. Factors such as weather, efficiency of the process and the technology involved have a significant effect on the amount of energy used for drying the grain, and the variation from one year to another can be very large, hindering to specify an accurate value of the energy. Therefore, it is important to note that the values used in this research are approximations of typical energetic values, and that particular factors can provoke them to alter differently.

<u>Number of crop dryers</u>

Regarding crop dryers, there is no information available about how many of them exist or are in use in Finland. A possible approach could be done with the information about the amount of Finnish farms that produce crops, where statistics are classified by their main production sector or by their agricultural output. According to LUKE statistics database (LUKE 2018b, LUKE 2018c), from the total number of 47.633 farms in Finland 15.197 produced cereals as their main output in 2018. When it comes to all farms that produce the grain, including those with other main outputs, statistics show that 33.764 units produced crops in 2018. However, these statistics have certain limitations, and farms with economic size lower than 2.000 € per hectare were not taken into account. That limitation complicates to obtain a precise number of dryers in Finland, and more complicated it becomes when considering that some farms do not have their own dryers. Taking into account those aspects, the number of dryers in Finland has been estimated at 35.000 in this work.

Annual harvest

In the last two decades, the average harvested yield in Finland has been 3,6 billions of kilograms, harvested in an area of on average 1 million hectares (TIKE 2014, LUKE 2018b). Although the harvested area has maintained relatively constant during the years, annual variations of the weather and other factors have caused significant changes in the yields per hectare and thus the total amount of harvested crops has varied between 2,6 and 4,2 billions of kilograms. The climatic conditions do not only affect to the amount of crop that every hectare of field is able to provide, and the energy that is needed to dry a ton of grain changes significantly depending on the ambient temperature or the air humidity. For those reasons, the data of annual yields does not provide a sufficient solid base to calculate a fair value of the energy consumed in Finland in crop drying.

Fuel oil consumption

The only information related to the energy use of crop drying in Finland has been found on LUKE statistics (LUKE 2018a), as part of the data about the energy consumption of agriculture and horticulture. Specific data about the fuel oil for the drying of cereals is provided for the years 2010, 2013 and 2016, in gigawatt hours of the consumed fuel. The data refers to the energy in the fuel itself and not to the produced heat, thus a factor of 0,9 has been applied to convert the energy of the fuel into the heat energy, based on typical efficiencies of fuel oil heaters (Hautala et al. 2013). As the average fuel oil consumption for the three years is 660 GWh, the average heat energy used to dry crops has been calculated at 600 GWh.

That estimation considers only the crop that has been dried with the fuel oil, meaning that other drying methods than the hot air drying are ignored, as well as other possible fuels that are used in the hot air dryers. However, it has been mentioned earlier that other methods or technologies for drying crops such as the ambient air drying are marginal in the context of the Finnish yearly grain production, especially in terms of energy consumed. In addition, other grain drying techniques normally use energy sources that are not based in fossil fuels, mostly electricity, making the hot air drying yet more relevant for this study due to its extended use and environmental concerns.

Besides the fuel oil, some hot air dryers use bioenergy in form of woodchips to produce heat. The number of crop dryers using wood chips in Finland in the year 2009 was estimated at around 100 (Metsäkeskus 2009), and even though their number has been recently increasing, it can be assumed that their total current energy consumption is insignificant compared to all the fuel oil consumed in the country. Therefore, the estimated consumption of 600 GWh has been assumed as the yearly annual energy consumption for drying crops in Finland, being aware of yearly variations and dryers with other energy sources.

When it comes to the timing of the drying, as mentioned earlier, crop drying period is usually between the mid-August and the end of September, and it can prolong until October in same cases. However, this does not mean that the drying happens every day of the drying period, and the operating days of the dryers are on average 20. Taking into account the length of the drying period and the actual drying days, this study has assumed that the above mentioned yearly energy consumption of crop drying occurs in a period of a month.

3.1.2 Solar energy production

The Finnish summer offers decent conditions for the solar energy production for several reasons. Long days can provide solar energy for many hours, good sunny days irradiate solar power of around 1.000 W per square meter and adequate temperatures keep the efficiency of the panels close to their optimum performance. As illustrated in Figure 10, the drying period at the end of the summer has still appropriate solar conditions to produce electric energy.

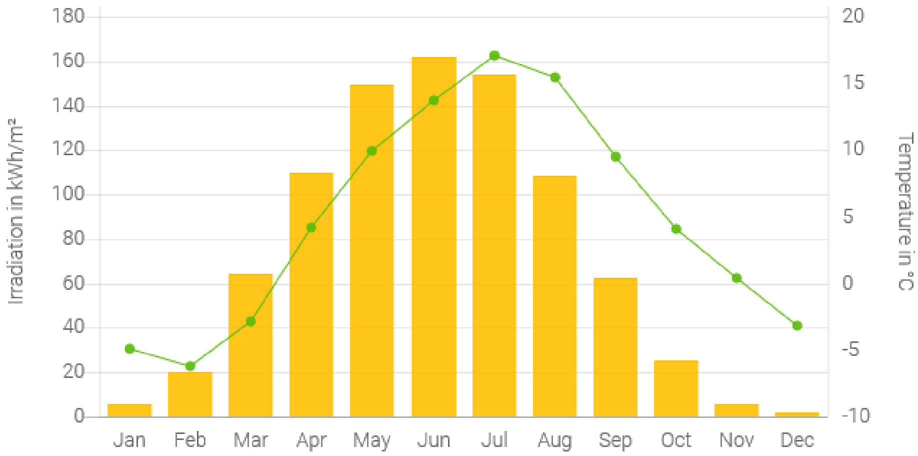

Figure 10: Monthly average solar irradiation and ambient temperature in central Finland for the whole year (PVSOL 2019)

In order to compare the available solar photovoltaic energy with the energy consumption mentioned above, values of the solar irradiation have been obtained from the PVGIS online tool (European Commission 2017). Monthly average data from Jyväskylä has been used because the location of the city represents the average latitude of crop producing farms in Finland (The Finnish cereal committee 2018), and a time period of ten years has been used from 2006 to 2015.

The orientation has been assumed to be South by default, that is, with an azimuth of 0°, and the global irradiation has been calculated at an angle of 30 degrees as it can be observed in Figure 11. The slope of solar panels may not be the optimum for the photovoltaic production, but it has been chosen for practical reasons and because it represents the most common slope of rooftops. In order to convert the solar global irradiation into the amount of electric energy that can be produced by the PV system, an efficiency of 17 % has been assumed for the solar cells and a performance ratio of 0,8 for the rest of the system including inverters, cables and other aspects. Therefore, the overall efficiency of the PV production has been assumed at 14 %.

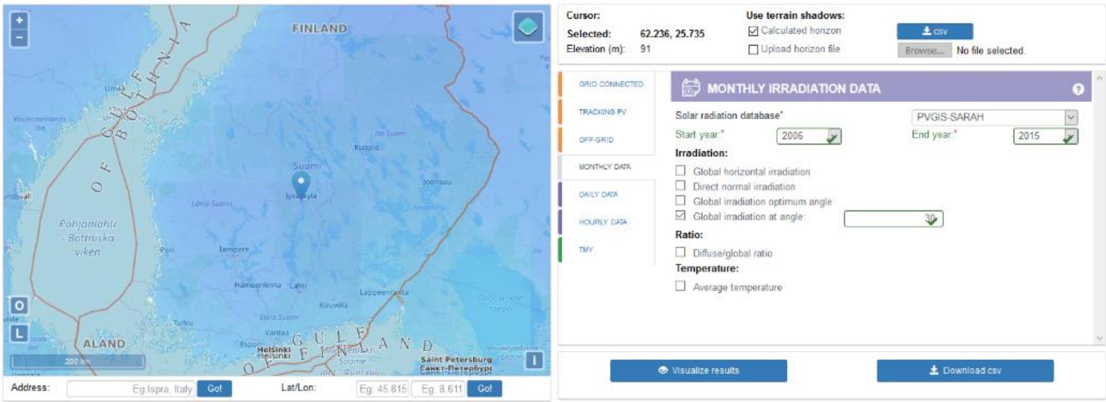

Figure 11: The chosen location and specifications of the PV system in the online tool PVGIS (European Commission 2017)

After obtaining monthly values for the photovoltaic energy production, the monthly production of the drying period has been calculated by the average of the months of August and September, considering that most of the crop is dried during those two months. Therefore, that value can be considered as the mean monthly solar PV production for the drying period, in this case 14,36 kWh per square meter. In order to estimate the amount of solar energy produced in the whole region, the average monthly production has been multiplied with the total rooftop available area.

When it comes to the total rooftop area, on the one hand, it has been estimated that a typical farm in Finland, including a house and two barns, can have around 500 m² of roof surface available for solar panels. On the other hand, the total roof surface of the buildings in the country that are out of the urban areas has been found to be 392 millions of square meters, from which 87 million corresponds to residential buildings (Haapaniemi et al. 2016). As mentioned above, those estimated rooftop areas have been used together with the solar production per square meter, in order to assess the potential production of the solar energy against the energy consumption of crop drying.

3.2 Solar PV and electricity in crop drying

3.2.1 Kasken tila

“Kasken tila” is a farm located in Kiikoinen, municipality of Sastamala, Pirkanmaa region. The farm has a grain dryer, shown below in Figures 12 and 13, where mostly oat is dried with an average of 600 tons per year. Around a fifth of that amount is from their own fields while the rest is brought from other producers. The dryer is used mainly between mid-August and the end of September, but depending on the harvesting conditions it also may be needed in the beginning of October. Besides the main drying period, the dryer is sometimes used at other times, especially for some exceptional drying of crops from other places.

Figure 12: The crop dryer in “Kasken tila”

Figure 13: The dryer, the heater and the solar panels

The dryer uses energy in two forms, as drying crops requires heat and the devices involved consume electricity. The heat in the form of hot air is obtained from a heater attached to the side of the drying silo, as can be observed in Figure 13. The heater is fed with wood chips obtained from the surrounding forests, and its nominal power is 800 kW. The heat is only used when the crop is being dried, but the electricity also is used at other times for additional tasks related to the drying process, when heating is not needed. The electricity is mainly imported from the distribution grid, but part of it is produced locally with two PV systems installed after August 2017. The electric energy consumption corresponds to the electrical devices such as elevators and ventilators that are part of the dryer and the heater. The process of drying crops consumes the largest part of the electricity, but some also is consumed at different periods to carry out other tasks, mainly ones related to crop handling in spring.

Tables 4 and 5 display the electric devices involved in the drying process and their nominal powers, with 70 electric kilowatts installed in the dryer and the heater. However, the devices usually have different operating times and the ones belonging to the heater have controllers for their optimal use, thus the electric power required in the process is always lower than the installed power.

Table 4: Electrical devices of the dryer

Device	**Units**	**Nominal power (kW)**
Main elevator	1	15
Secondary elevator	1	7,5
Pre-cleaner	1	2,5
Base extractor	1	2,2
Feeder	1	1
Dust extractors	2	1,75
Grain spreader	1	3,5
Dust extraction fan	1	0,5
Dust extraction fan (base)	1	0,3
Screw conveyor	1	1,5
Extra fan for cooling	1	7,5
Total dryer	**45 kW**	

Table 5: Electrical devices of the heater

Device	**Units**	**Nominal power (kW)**
Fans for the heat	2	7,5
Wood chip feeder	1	2
Motors	3	1,5
Spiral for the ashes	2	1,2
Fan for the exhaust smoke	1	1,25
Air fans	2	0,25
Total heater	**25,65 kW**	

As mentioned, the farm has two PV systems since 2017. One of them, with an installed power of 10 kWp, includes 36 panels and is located on the roof of the drying silo as seen in Figure 13. The other PV system is installed on the roof of the workshop, with a peak power of 20 kW and 72 panels. Both systems are connected to the grid with individual inverters, and they send the produced electricity to the consumption upon the needs, or they export it to the distribution grid. In the second case, the energy is sold to the energy retailer. Due to technical problems, a complete production data of the solar panels has not been possible to obtain.

The electricity consumption data of the farm has been obtained for the years between 2013 and 2018, as no information was recorded for the years before 2013. The data has been provided by the contact person at the farm, and it is available in the online service of the energy retailer in the form of hourly and daily values. The measurements are from a unique automatic meter reader (AMR), there is no distinction between different consumptions and it only measures the flow of energy, that is, what is taken from the grid and what is sold back to the grid. As data of the PV production has not been possible to measure, the only information about the solar energy production in the farm is what can be seen as sold to the grid. However, the electricity from the solar panels that has been consumed in the farm is not recorded in the AMR as no measurement of it exists, thus a complete data of the solar PV production has not been possible to obtain. Therefore, the consumption data of the years 2017 and 2018 has not been considered for the analysis, and only years 2013, 2014, 2015 and 2016 have been used.

Roof availability

Table 5 displays the estimated areas of the rooftops in the farm that could be available for the solar panels. Available rooftops have been defined mainly based on their orientation, but the slopes of the roofs have been also taken into account. Rooftops facing towards the Southeast, the South and the Southwest have been assigned as suitable, with slopes of up to 60 degrees. In the case of horizontal roofs, as they have no azimuth, the direction of their longest sides have been considered. The areas have been calculated with *Google Earth*, and the directions and tilts have been estimated based on the site visit and the satellite images.

Table 5: Estimated available rooftop area in the farm

Building	**Available area (m²)**	**Azimuth/Direction**	**Slope (°)**
House	40	Southwest	40
House 2	90	Southeast	40
Workshop	200	Southwest	30
Barn	180	Southwest	40
Shed 1	240	North-South	0
Shed 2	180	North-South	0
Shed 3	170	Southwest	30
Shed 4	180	Southeast	30
Dryer	60	Southeast	50
Office	20	Southeast	40
Total	**1360**	-	-

3.2.2 Consumption

The obtained consumption data of the farm includes the dryer, the domestic as well as other energy uses, and there is no separated data of the electricity use of the dryer. The domestic electricity consumption remains relatively constant throughout the day and the year, due to the use of freezers and other appliances, with an average value of 4 kW. That constitutes, on a daily basis, an average domestic energy consumption of around 100 kWh. Other electricity uses that can be, for example, drillers or other electric machines do not suppose large amounts of energy. They are used for relatively short time periods and irregularly, thus are insignificant compared to the levels of electricity consumption of the dryer.

When drying crops, the consumption of the electrical devices is usually around 16 and 30 kW, with averages of 20 kWh per hour and 400 kWh per day. That amount varies depending on both internal and external conditions. Internal conditions are, for example, the amount of dried crop or its moisture level, while the external conditions are, for instance, the outside temperature and the humidity of the air. Nevertheless, the elevator of the dryer needs to be operating for the drying, and that sets the minimum consumption level of the drying process at 15 kW. Besides the elevator, other devices also have to be working for the drying of crops, and considering the base domestic consumption of 4 kW, it can be assumed that the whole farm consumes a minimum of 20 kW in the drying process.

As mentioned before, electricity is not used only when the crop is being dried – i.e. when the heater is working –, and tasks such as sorting or transporting the grain are carried out at other times. On average, 16 kW are used for the works that are done without the need of the heat. Those tasks are carried out at different periods that vary depending on the needs of the crop and the weather conditions, and although there is no periodic or predictable time for it to happen, spring is the season when most of these tasks are performed. When it comes to the total annual energy consumption, the farm consumes on average 50.000 kWh of electricity, from which around 10.000 kWh correspond to drying.

The electricity consumption of the farm is illustrated in the following figures. Figure 14 shows the hourly data of the electricity consumption of the farm in 2016. There, it can be observed that a minimum amount of energy is consumed during the whole year, corresponding to the mentioned domestic consumption of 4 kW. Few exceptions can be seen with lower consumptions than the basic domestic use, and they represent power outages or other rare problems. Peaks also can be identified, mostly in early spring and late summer. The peaks before and during the summer, on the one hand, correspond to the use of the dryer for the crop handling and some exceptional drying, but also to other electricity uses in the farm. The high concentration of peaks at the end of the summer, on the other hand, correspond to the drying period, i.e. the main electric consumption of the dryer.

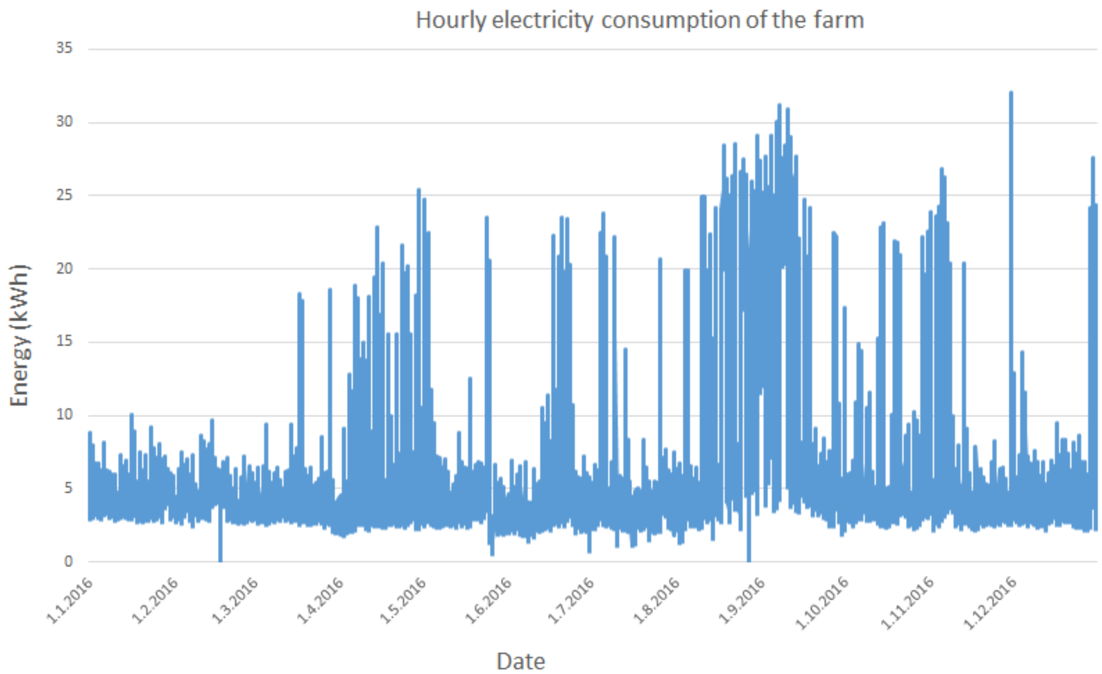

Figure 14: Hourly data of the electricity consumption in 2016

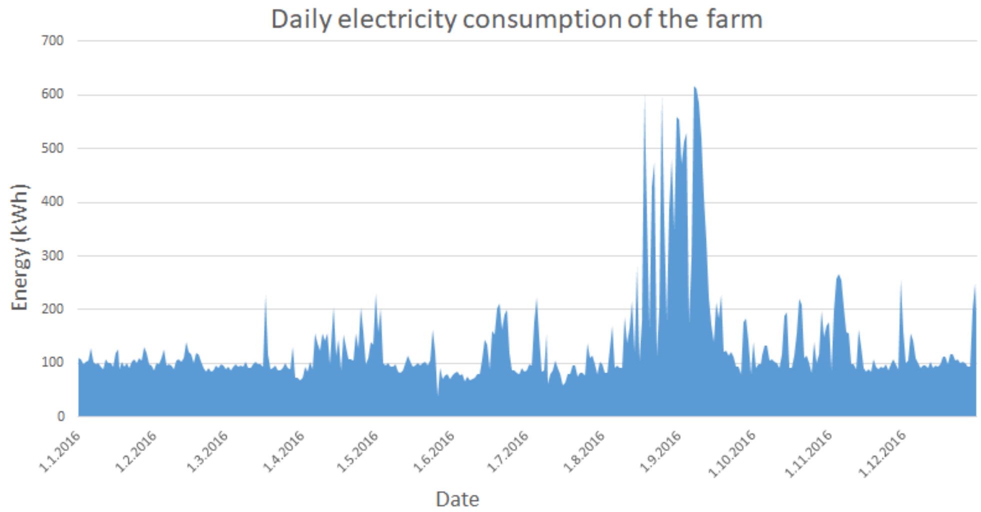

Figure 15: Daily data of the electricity consumption in 2016

The hourly-based data provides interesting information of the electricity use in the dryer, and gives a good temporal and quantitative understanding about the specific uses of the electricity. However, the daily data offers a clearer picture of the energy used in the drying process, as Figure 15 describes. Here, the distinction between the drying period and the rest of the year is more obvious than in the hourly-based graph, and is easier to identify the temporal and quantitative characteristics of the drying. Observing to it, other energy consumptions than the drying period become less significant, and more importance takes the energy consumed during crop dry.

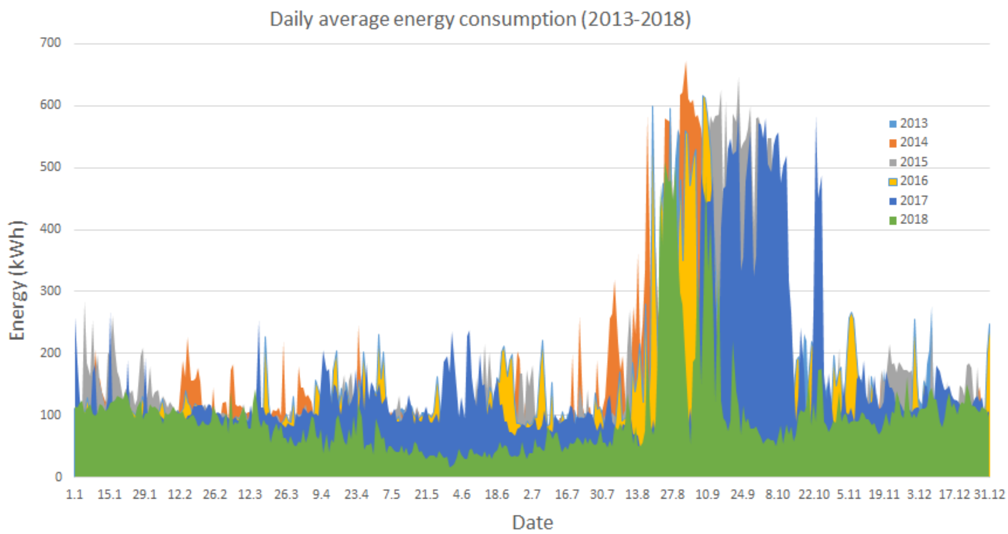

Figure 16: Daily electricity consumption of the farm between 2013 and 2018

The graph in Figure 16 describes the electricity consumption of the farm for all the years with available data, and clearly shows how the drying is concentrated in a similar period every year, with small changes among them. As the solar panels were installed in the end of August 2017, solar contribution of that year cannot be estimated from the data available. The data from the year 2018 shows the effect of the solar PV production in the energy consumption, with a clear decrease of the imported energy in summer. Besides, the energy consumption in the drying period of the same year also is lower compared to the previous years. However, the contribution of solar energy is difficult to estimate in that decrease because the year 2018 was unusually dry and the crop yield was smaller than normally, entailing that the energy consumed for the drying also was smaller than in the previous years. Therefore, no more conclusions than the drop in the purchased electricity in summer can be obtained for the data available.

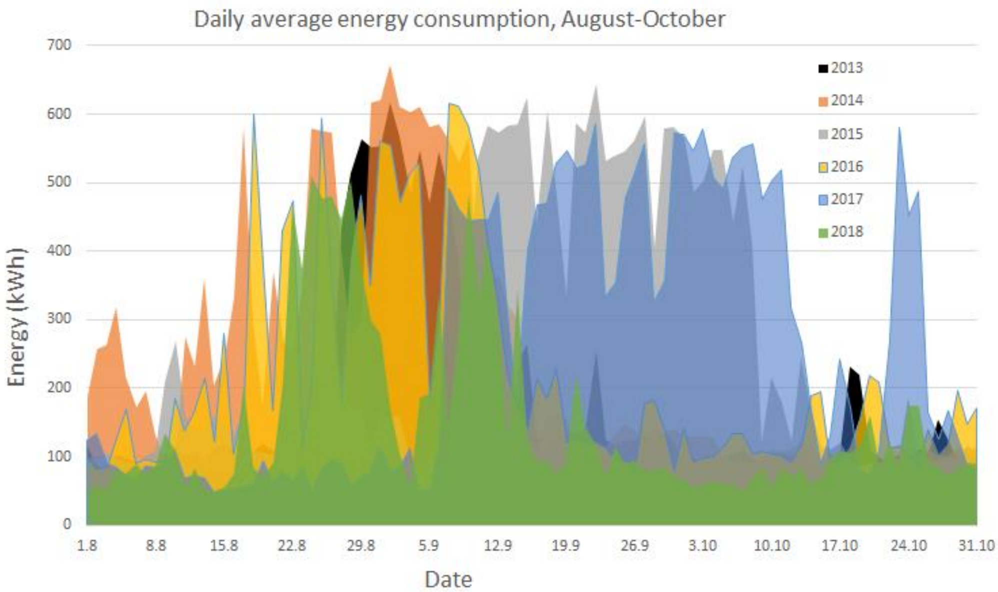

Figure 17: Daily electricity consumption of the farm in the drying period

In conclusion, the dryer consumes on average 400 kWh of electricity per day for the drying, and around 10.000 kWh in the whole period. The daily consumption of the whole farm rarely goes above 600 kWh, meaning that the dryer usually does not consume more than 500 kWh per day. That can be seen in Figure 17, where a closer look at the drying period shows the differences of the amount of energy consumed by the dryer as well as the different timing of the drying. As mentioned before, the drying usually happens between the middle of August and the end of September, as Figure 17 shows, but also sometimes in October. The same way, the number of drying days – i.e. the days where the drying has been carried out during the drying period – varies significantly, and in this case values have been found to be between 13 and 31.

3.2.3 Solar production

Once the electric energy consumption of the dryer has been defined, the next step has been to estimate the solar production in the location; that is, how much electricity could be produced from the solar energy in the farm. It has to be mentioned that this work has not intended to find a solution for a concrete case, but has rather looked at the possibilities and potentials of the solar energy with a more general perspective. Therefore, specific physical and other characteristics of the farm and the dryer have not been considered, with the intention of focusing more on other aspects more interesting for this work.

The same way as in the previous section, the solar energy production has been calculated with the online tool PVGIS. Figure 18 shows the location and the chosen values. In this case, the location of the farm has been set as the reference location for the solar data.

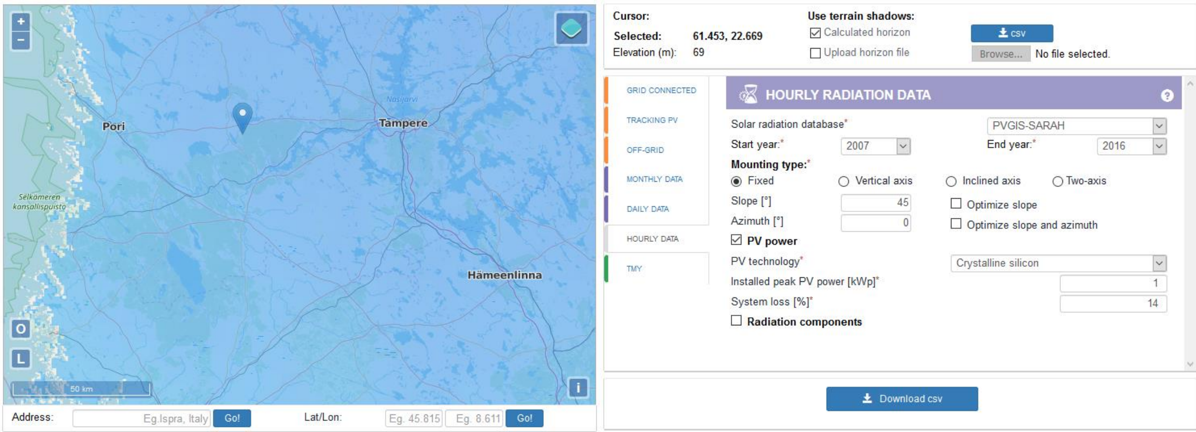

Figure 18: The location and specifications of the PV system in the online tool PVGIS (European Commission 2017)

In this case, average values based on several years were used for basic comparison, but not for the main simulation. In the simulation, values for each year —2013, 2014, 2015 and 2016— were considered because using the average values would ignore the stochasticity of solar energy. If the average values are used, the simulated PV production represents the average solar radiation for each day but does not represent the real temporal profile of the solar radiation for several days because the days with no solar radiation are ignored.

The produced PV power has been calculated in reference to the production of the installed PV power of 1 kWp with system losses of 14 %, and assuming that the solar panel is facing South —azimuth of 0°—. When it comes to the optimum angle, a slope of 43 degrees would provide the best performance if the whole year is considered, and the optimum angles for different periods are displayed in Table 6. There, it can be observed that the best slope changes depending on which period is considered, with a correlation between the slope and the time of the year.

Table 6: Optimal slope at different periods

Month or period	Best slope (°)
August	30
September	50
October	60
August-September	43
August-October	50

On average, the optimum angle for the drying period could be estimated at 45°, as August and September are the most important months but October also counts. Therefore, and for practical reasons, a slope of 45° has been chosen. A slightly higher slope would improve the solar use in the latter part of the drying period, possibly increasing the share of solar energy when drying. However, this work does not aim to find an optimal solution and rather intends to evaluate the potential of solar energy in a general level, adjusting to what is available.

Figure 19 shows the daily average solar PV production and its polynomial average of the whole year, based on the data of ten years from 2007 to 2016. It represents the energy that an installed kilowatt of PV panels would produce. With a PV efficiency of 17 %, that would equal to 5,88 m² of panel surface.

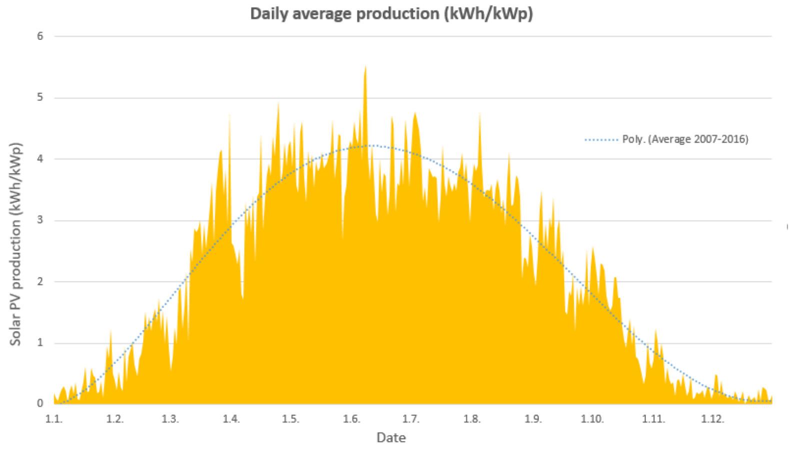

Figure 19: Daily solar PV production and its polynomial average

Figure 20 shows the hourly average solar PV power for the 15th of September for the years between 2007 and 2016. In other words, it describes the average daily solar production profile for the middle-end of the drying period.

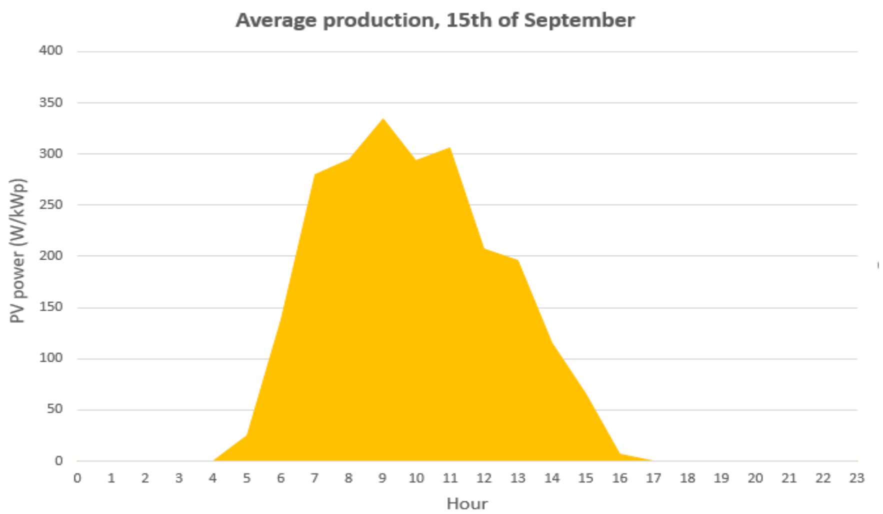

Figure 20: The hourly average of the solar PV production, 15th of September

Although the profile of the yearly solar production shows a curved line, during the drying period the decrease is virtually lineal as Figure 21 describes.

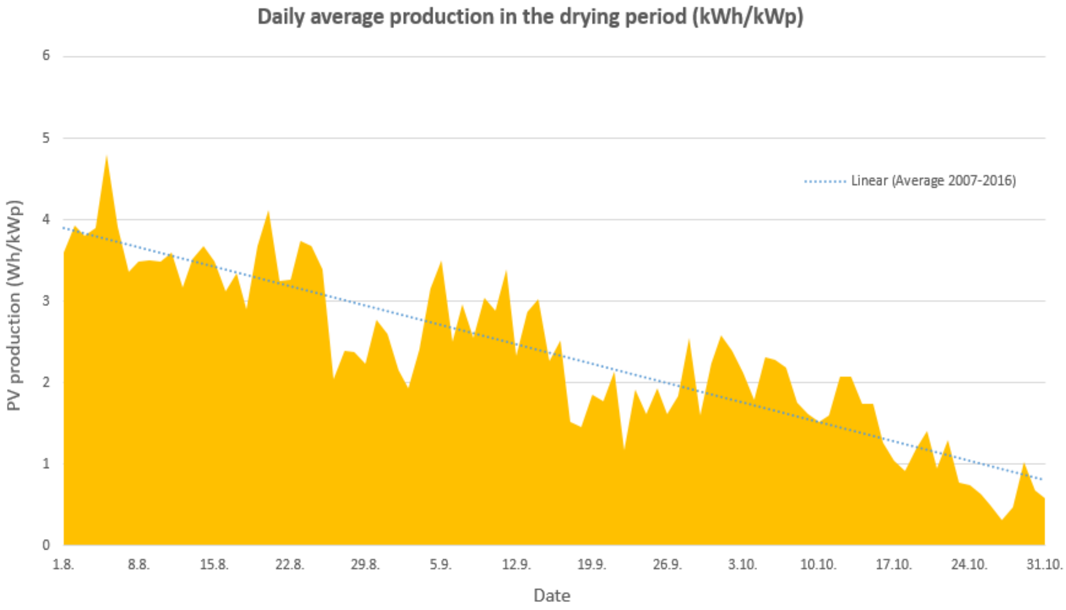

Figure 21: Daily average production during the months of the drying period

3.2.4 Production versus consumption

After defining the consumption and production profiles, the next step has been to compare one to each other in order to estimate the amount of consumed energy that could be covered with the solar production.

First, the average values of both consumption and production have been compared as seen in Figure 22. For the solar electricity production, three sizes or installed capacities have been simulated with peak powers of 50, 100 and 150 kW, multiplying the production values of the 1 kWp photovoltaic system with the respective installed peak powers. Similarly to the solar production data, the consumption profile does not represent a normal profile of the energy use by the dryer since it entails the average values of several years and exclude the temporal differences. Nevertheless, it is useful to compare the period with the largest concentration of the energy consumption with the average PV production of the same period.

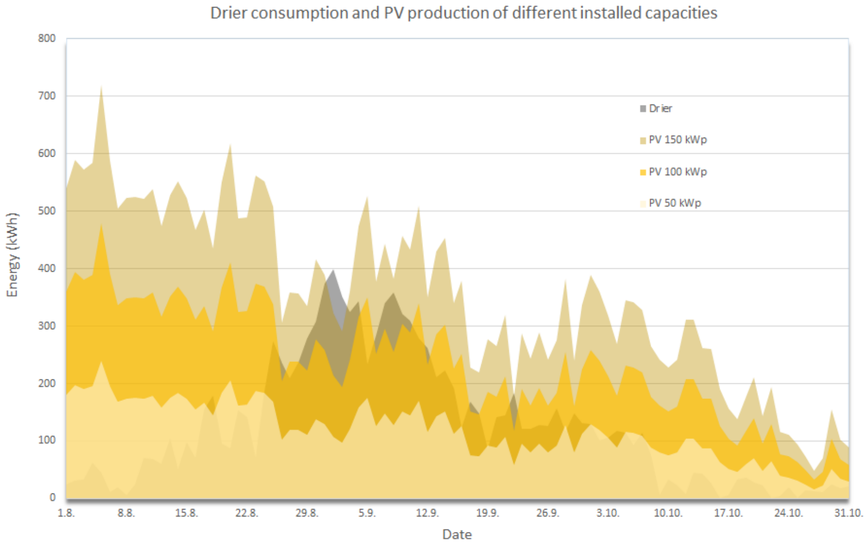

Figure 22: Average values of the consumption and the production with different PV sizes

Continuing with the mentioned, the altering temporal and quantitative features of the energy consumption complicates the creation of an energy profile that accurately represents the energy use in the dryer. That is, the profile of the average consumption differs significantly from the actual consumption profile. The same way, the average solar production of several years gives an insight about the solar energy available at that period, but does not represent the actual production profile of the solar energy. That is because the average calculations hide days with no solar production or days where the dryer has not been operating, and assumes that there is everyday consumption as well as production, as it can be observed in Figure 22. Therefore, the comparison has been made year by year for the available data, in this case for the years 2013, 2014, 2015 and 2016.

The following graphs in Figures 23, 24, 25 and 26 show the actual daily consumption and the calculated daily PV production in the drying period for each of the mentioned years.

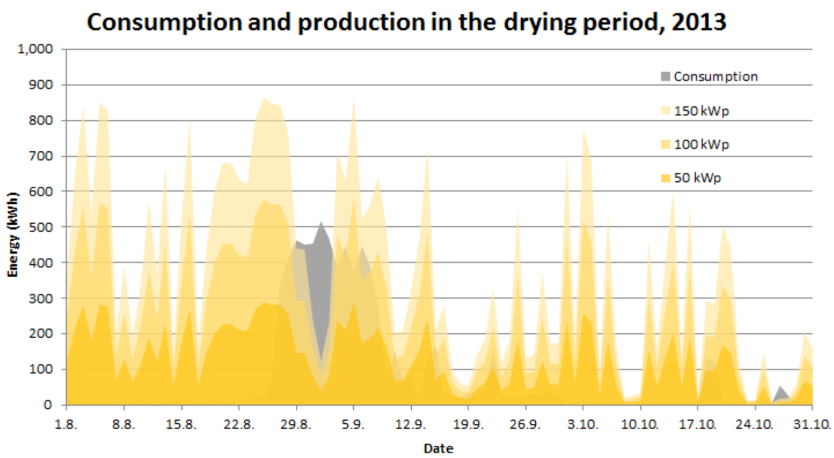

Figure 23: Consumption of the dryer and solar PV production during the drying period of 2013

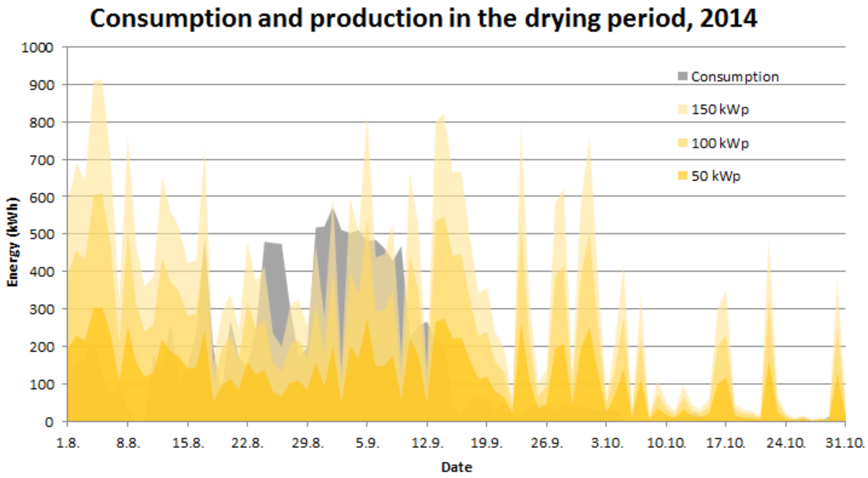

Figure 24: Consumption of the dryer and solar PV production during the drying period of 2014

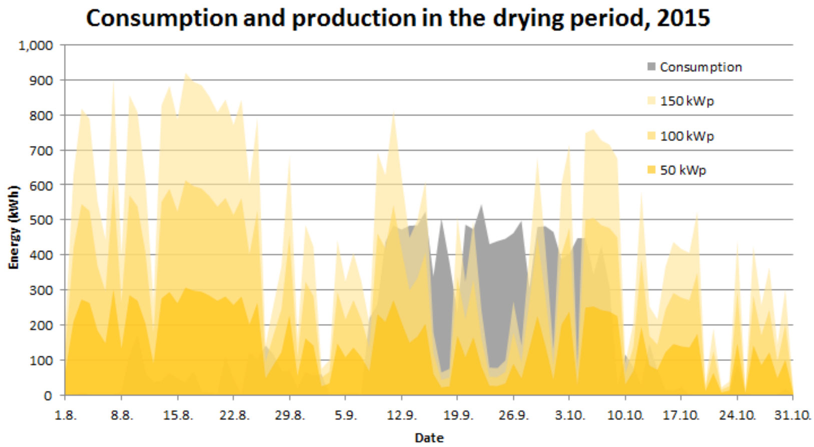

Figure 25: Consumption of the dryer and solar PV production during the drying period of 2015

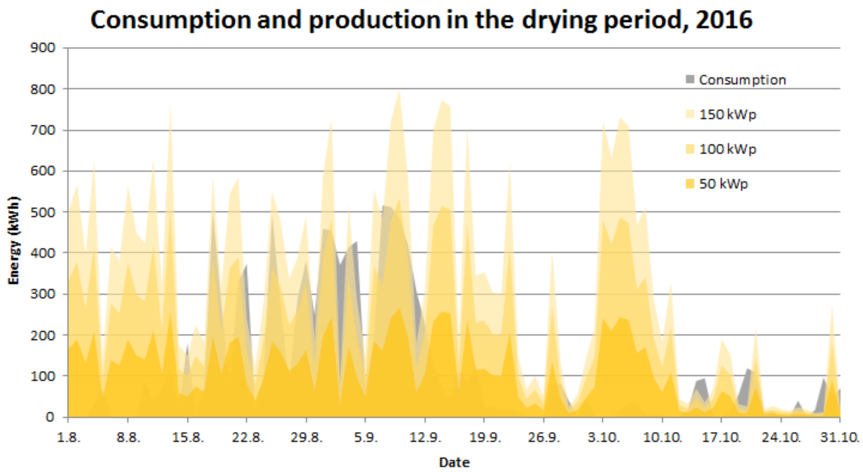

Figure 26: Consumption of the dryer and solar PV production during the drying period of 2016

Compared to the profiles with average values, the graphs above show that both the consumption and the solar production vary significantly during the drying period. Despite the stochastic consumption and production profiles, the share of the solar energy with the consumption stays relatively similar from one year to another for the data available. Table 7 displays the percentages of the consumed energy covered by the PV production.

Table 7: Share of the solar production with the consumption

Consumption covered with solar energy (%)			
Year	**PV system size (kWp)**		
	50	**100**	**150**
2013	53	78	87
2014	49	73	86
2015	40	65	75
2016	48	78	89

The above figures show the amount of available energy and compare it to the consumption of the dryer. However, the comparison is based on daily values that do not take into account the temporal differences; that is, it does not consider that the solar energy is produced only during the day and that the consumption also occurs during the night. That type of comparisons can be made upon two assumptions. One assumption is that both the energy consumption and the energy production occur simultaneously, and the other is that the excess energy can be stored for its later use. The first one, known as demand response, entails that all the energy has to be consumed during the day when the sun irradiates. There, it has to be considered that as the dryer also is used during the night, its maximum working capacity does not let it to concentrate all the consumption in the period when the sun shines. Although the dryer could shift the demand to a certain degree, it cannot do the same amount of work using the half of the time.

The difficulty of pairing consumption and production can be observed in Figure 27 where the consumption and the production are compared in an hourly base. The graph shows that the 50 kWp system could almost cover all the energy used at that moment, while the higher installed capacities could produce even more than needed. Shifting the energy consumption from the night to the daytime would compensate the differences and facilitate to cover the energy use with the solar energy. However, the electric energy consumption is constrained to the drying process, and other aspects of the crop production have to be considered in order to analyse the possibility of shifting crop dry. That area can have an interesting potential, but it is beyond the scope of this work thus the first assumption is not considered further.

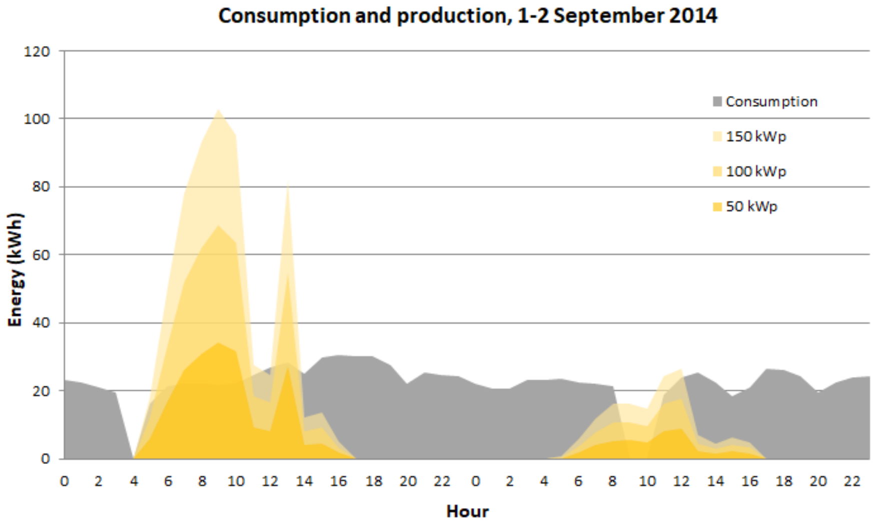

Figure 27: Consumption of the dryer and the solar PV production on 1st and 2nd of September 2014

The second assumption, as mentioned, entails that the excess energy produced by the PV panels is stored to use later at times when there is consumption without production. This assumption has been taken further by comparing the consumption and the solar production, but adding the use of electrical battery storage. For that, the hourly PV production data from the PVGIS online tool has been used, and a simulation of the energy storage has been carried out using Excel. The simulation includes the state of the storage at every hour for the four years used before, and considers the imported energy as well as the excess energy.

3.2.5 Batteries

Batteries are currently the most widely used electrical storage system globally. They promise significant potential for decarbonizing the energy and transport sectors, due to their accessibility that is constantly improving. Their use, in combination with solar photovoltaic production, is already enabling to decarbonize the energy system at the level of the domestic energy consumption and mini-grids, and they have shown the capacity to bring important socio-economic benefits (IRENA 2017). High power densities and high conversion efficiencies make batteries to be the most affordable system to store the energy for purposes such as maximising the self-consumption and shifting peak demands (Weniger et al. 2016).

The use of batteries has mostly increased in the sector of the electric mobility, but stationary batteries are rapidly increasing their presence in the residential level and they are becoming more common on the utility scale (IRENA 2017). Besides, stationary batteries provide good characteristics to improve the accessibility of electricity when combined with the solar energy or other renewable sources. Simultaneously, they increase the usability of the distributed energy production and they offer other benefits such as a better power quality or stability to local grids. In that way, batteries are key in the transformation of the energy system by providing new possibilities of consuming and producing energy, for example by facilitating consumers to become prosumers (Juntunen 2014). The grid parity of solar photovoltaic energy has been possible in some markets as a result of using battery storage, and the self-consumption of solar energy may become more preferable than consuming energy from the grid as economic conditions improve further in the future (Keiner et al. 2019).

Different types of batteries are used for different purposes as each of them provide energy with certain characteristics. Lead-acid batteries have predominated the sector of PV-battery systems as they are better than lithium-ion batteries for mid-term storage (Weniger et al. 2016), but the latter ones are becoming more common as the short-term use of the storage is increasing in the area of renewable energies, including photovoltaic energy. In addition, Li-ion batteries have remarkably improved with regard to their volumes and prices, and nowadays they are the usual type of batteries used by prosumers (Keiner et al. 2019). However, due to different needs for storage of energy sources and energy uses, several storage characteristics will be required and thus batteries of different types will have to be available in the market (IRENA 2017).

As mentioned, batteries have high conversion efficiencies compared to other storage systems and that is one of the main reasons of their extended use. Their charging and discharging efficiencies can reach values of around 97 %. That is, they can provide almost all the energy they have received. In this case, the simulation of the energy production and consumption is rather comparative than technical, and the efficiency has not been taken into account, or it can be assumed that the efficiency is 100 %. Similarly, the depth of discharge has not been considered for the chosen sizes of the battery storage. Hence, it has to be noted that the installed storage capacity mentioned in the simulation should be understood as the actual capacity of the battery.

3.2.6 Simulation

Using the hourly-based data available, storage capacities of 50, 100, 150 and 300 kWh have been simulated in combination of each size of the PV system, in this case 30, 50, 100 and 150 kWp. The use of solar energy without any storage also has been considered in the simulation, represented by the storage capacity of 0 kWh. The excess energy that is not consumed nor stored in the batteries is assumed to be sold to the distribution grid.

The PV capacity of installed 30 kWp has been chosen because the farm already has solar panels with the same installed capacity. At the same, since the hourly consumption can reach values of 30 kWh, a PV system of at least 30 kW would be needed to cover the hourly energy use. The installed PV capacities of 50 and 100 kWp have been chosen because they represent PV systems that can be installed in relatively large farms with available roof surfaces of 300 and 600 m^2 consecutively, assuming panel efficiencies of around 17 %. Earlier in this work, it has been estimated that a typical farm with a house and two barns has an available roof surface of around 500 m^2. In the case of the installed capacity of 150 kWp, the surface area would be close to 900 m^2. Such size of the PV system has been found to be a reasonable size for large farms such as the reference farm used in this section.

As mentioned, the different storage capacities have been chosen to analyse the variation in the suitability of the storage for the solar energy when used for crop dry. The criterion to choose the different sizes of the storage for the simulation are based on the assumption that it should provide energy during the night or cloudy moments. The average hourly consumption of the dryer is 20 kWh, but in some days the consumption reaches values up to 30 kWh. Therefore, the size of the storage has been chosen based on the assumption that it should provide more power than the usual average, and for the entire night; that is, 25 kWh for 12 hours. That supposes the largest storage capacity considered for the simulation, 300 kWh.

Each year has been simulated individually like in the previous comparisons, and then averages of the four years have been used for further calculations. In this case, the simulation has been made for two cases: one case considering only the energy use in the dryer and the other case considering all the consumption of the farm. For the first case, other energy uses than the dryer have been excluded by using only hourly data higher than 20 kWh and then resting 4 kWh to each. That exclusion is based on the previously stated energy consumption levels, where the average hourly consumption of the farm without the dryer is 4 kWh and where the consumption of the dryer is always over 15 kW.

The state of the battery at the end of every hour (h) has been calculated by summing the level of energy in the battery in the previous hour ($E_{storage,h-1}$) with the solar production of that hour ($E_{produced,h}$), and resting the average consumption of the dryer ($E_{consumed,h}$) of the same hour, with the following expression (1):

$$E_{storage,h} = E_{storage,h-1} + E_{produced,h} - E_{consumed,h} \quad (1)$$

where

h — hour of the year

The excess and lack of energy also have been calculated. The excess energy is what has been produced but has not been consumed nor stored, and the lack of energy is what has been imported from the grid when the solar production and the battery storage have not provided sufficient energy. In other words, the excess is what has been exported to the grid while the lacking energy has to be imported from the grid. They have been calculated the same way as the storage, but with the difference of resting the new energy level of the storage. In both cases, a positive result means that there is excess energy while a negative result expresses the need of importing energy. The following formulae have been used to calculate the excess energy (2) and the imported energy (3):

$$E_{excess,h} = E_{storage,h-1} + E_{produced,h} - E_{consumed,h} - E_{storage,h} \quad (2)$$

$$E_{lack,h} = E_{storage,h-1} + E_{produced,h} - E_{consumed,h} - E_{storage,h} \quad (3)$$

3.2.7 Economic calculations

Once the simulation of the batteries has been done, the next step has been to make the economic calculations in order to compare the economic viability of the different combinations of PV and storage.

The net present value (NPV) and the discounted payback period have been calculated for every combination, including the default case. The default case, also mentioned as the reference case, is where no solar panels and thus no battery storage is taken into account, meaning that all the energy is imported from the grid. Other cases are the different installed capacities of the PV power without the storage, and each of them with every size of the storage. That is, all combinations have been simulated for the installed PV capacities of 30, 50, 100 and 150 kW, and for the storage capacities of 0, 50, 100, 150 and 300 kWh.

<u>Net present value</u>

When it comes to the net present value, absolute and relative values have been calculated. In the absolute NPV (NPV_{abs}), each situation has been calculated separately including the reference case where no investment is considered. For the relative NPV (NPV), just NPV from now on, the value of the default case has been set as zero and the other cases have been calculated based on their difference to the reference case. That is, the (relative) NPV of each combination has been calculated by resting its absolute NPV with the absolute value of the reference case ($NPV_{abs,ref}$). Being all the net present values in relation to the default case facilitates the comparison among the different types of installations, but has to be taken into account that they do not represent their actual value. They rather represent the difference of their values in comparison with the reference case —where all the energy is imported from the grid.

Thus, the following formulae have been used to calculate the absolute (4) and relative (5) net present values:

$$NPV_{abs}(i,n,t) = \sum_{t=1}^{n} \left(\frac{cash\ flow}{(1+i)^t}\right) - Investment \tag{4}$$

$$NPV = NPV_{abs} - NPV_{abs,ref} \tag{5}$$

where

abs — the absolute value
i — the discount rate
n — the lifetime of the system
t — the number of years
ref — reference case

The yearly cash flow used in the computation of the NPV is the difference between the cost and the revenue of the energy for that year. The cost of energy is what has been paid to the distribution company for the consumed energy, and is the result of multiplying the price of the energy with the imported energy in the same year. The revenue of energy is what the distribution company pays for the energy sent to the grid, and is the amount of sold energy multiplied by the price of selling a kilowatt-hour to the company. As stated before, it has been assumed that all the excess energy is sold to the grid, thus the sold energy is considered equal to the excess energy.

The cash flow has been calculated as follows (6), including the revenue from the energy (7) and the cost of the energy (8):

$$Cash\ flow = Cost\ of\ energy - Revenue \tag{6}$$

where

$$Revenue = Price\ of\ sold\ energy\ \left(\frac{€}{kWh}\right) * Sold\ energy\ (kWh) \tag{7}$$

$$Cost\ of\ energy = Price\ of\ bought\ energy\ \left(\frac{€}{kWh}\right) * Imported\ energy\ (kWh) \tag{8}$$

Logically, the default case has the largest cash flow of all cases as the energy is only bought from the grid and never sold back. For the other cases, the larger the PV system is the lower the cash flow will be because less energy will have to be bought from the grid and more energy will be sold back. The opposite occurs with the initial investment where two types of costs have been considered, one for the PV system and the other for the batteries. In both cases, the initial cost becomes larger as the installed PV or battery capacity increase, and no investment is made in the default case.

Discounted payback period

The same way as the net present value, the discounted payback periods of the different cases have been calculated in relation to the default case. The payback period, however, cannot be computed for the default case, and a different cash flow has been used to make the calculations. For that, the relative cash flow has been used, using the saved money instead of the cost of energy. That is, the relative cash flow has been obtained by the summing the energy revenue with the saved money. The saved money, or the savings, is the price of the bought energy multiplied with the saved energy, where the latter one is the reduction in the consumed energy as a consequence of using solar energy. In other words, the saved energy is the difference in the imported energy between the default case and the rest of cases.

The relative cash flow (9) has been calculated as follows, using the formula of the revenue (7) expressed above and the savings (10):

$$Relative\ cash\ flow = Revenue + Savings \tag{9}$$

where

$$Savings = Price\ of\ bought\ energy\ \left(\frac{€}{kWh}\right) * Saved\ energy\ (kWh) \tag{10}$$

The discounted payback period is the number of years the system needs to cover the investment. In order to calculate the period, discounted yearly cash flows have been summed year by year, until their total sum equals to the investment. Therefore, the last year that has been summed (*T*) defines the discounted payback period, calculated as follows (11):

$$Payback\ period_{disc.} = T \quad when \quad \sum_{t=1}^{T} \left(\frac{Relative\ cash\ flow}{(1+i)^t}\right) = Investment \tag{11}$$

where

i — the discount rate
t — the number of years

Estimated variables

In order to calculate different costs in the simulation, values of several variables have been estimated. The prices of energy have been estimated based on the data from the Finnish Energy Authority (Energiavirasto 2019), for both prices of the bought and the sold energy. The price of bought energy has stayed relatively constant with values between 0,12 and 0,13 €/kWh from 2010 to 2018. However, as the blue line shows in Figure 28, the price of electricity has increased before and after that period, and has a general increasing trend for the current century.

The price used in the simulation has been estimated by calculating the average of the first quarter of 2019, with a result of 0,14 €/kWh. It has been assumed that it will remain constant for the following years. Similarly, the same source has been used to obtain the price of the energy sold to the grid, but based on different energy prices. In this case, when energy is sold to the grid the distribution company pays a price that is a certain percent lower than the SPOT price. Considering the development of the SPOT price in the last decade, illustrated with the orange line in Figure 28, it has been estimated that the average price for the sold energy is 0,05 €/kWh. That value has been used in the simulation, with the assumption that it will remain constant in the following years.

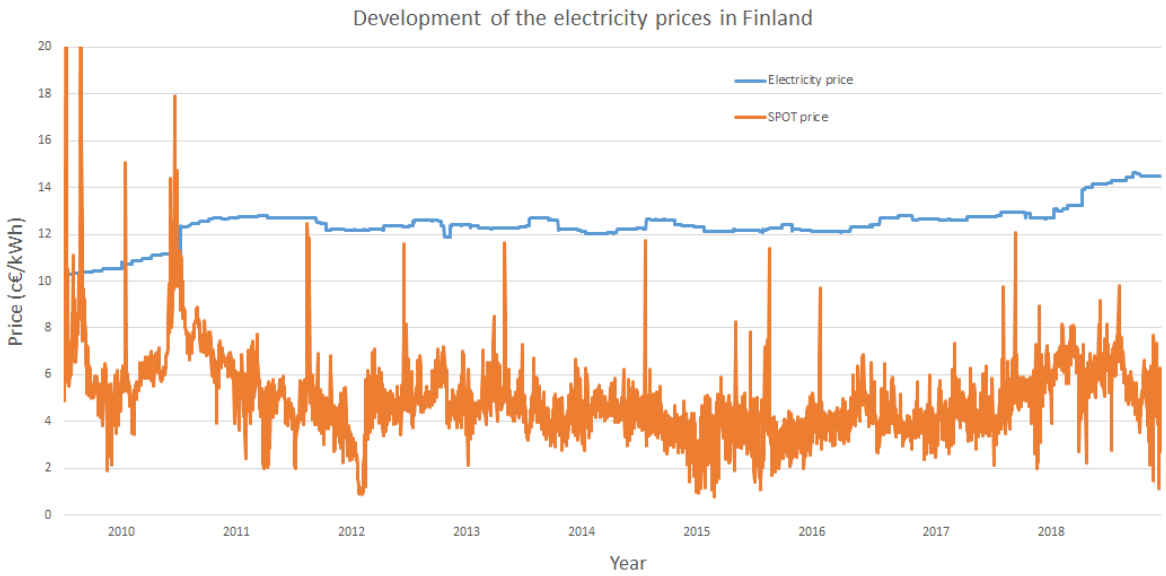

Figure 28: The development of the energy and SPOT price in the last decade (Energiavirasto, 2019)

The cost of the investment, as mentioned before, has been estimated considering costs of both the PV system and the storage system. Solar energy technologies are in constant development, their costs have decreased significantly since they have been commercialized and trends show that their prices will keep decreasing in the future. PV systems with battery storage have already reached grid-parity in some cases, and it is estimated that the capital cost of rooftop photovoltaic panels will halve in the next 20 years, compared to the estimated cost of 1360 €/kWp in 2015 (Keiner et al. 2019). In this work, a turnkey cost of 1300 € per installed kilowatt hour peak has been assumed for the PV system, based on market values of recent years (Auvinen & Jalas 2017).

In a similar way, the cost of stationary batteries is expected to cheapen significantly in the coming years as Figure 29 shows, with an estimated cost of three times lower than their current cost by 2040 (Keiner et al. 2019, Pöyry 2017). The price of stationary batteries vary depending on the battery type and other factors, and current prices are on average around 500-600 € per installed kilowatt hour of capacity (kWh_c). However, those prices apply to batteries that are smaller than the ones used in this work, and very limited information is available about the batteries with larger capacities. In this case, the cost of storage has been based on a study about the usability of the electric energy storage combined with solar PV for a farm, where an approximate cost of 900 € per installed kilowatt hour of storage capacity was calculated (Wikstedt 2018).

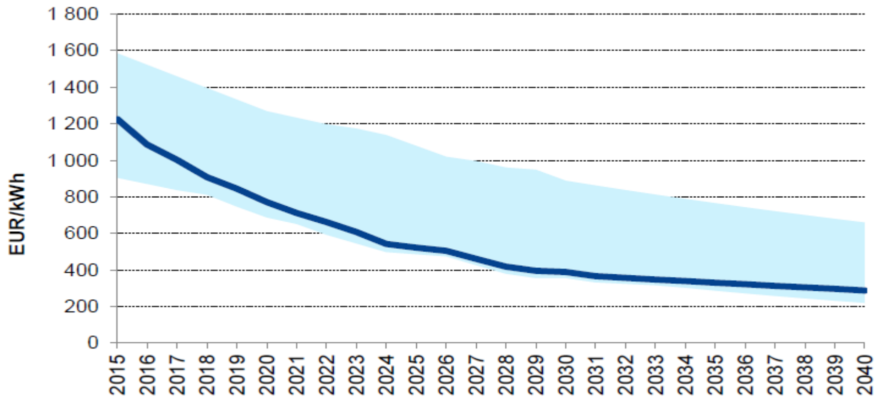

Figure 29: Future estimation of the price for battery systems (Pöyry 2017)

Besides the monetary variables, few other assumptions have been made for the economic calculations. The lifetime of the system has been assigned to be 25 years, based on standard values of PV systems and stationary battery systems available in the market (Keiner et al. 2019, Tesvolt 2015). The discount rate has been estimated at 2 %, and the support for the investment at 40 %. All the variables mentioned above are summarized in Table 7.

Table 7: The estimated variables used in the simulation

Variables	**Unit**	**Value**
Price of bought energy	€/kWh	0,14
Price of sold energy	€/kWh	0,05
Price of the PV system	€/kWp	1.300
Price of the storage	€/kWh$_c$	900
Lifetime of the system	years	25
Support for the investment	%	40
Discount rate	%	2

Finishing with the calculations, different price scenarios have been simulated by changing each economic variable, and new discounted payback periods have been calculated with the new values displayed in Table 8. For each price scenario, only one variable has been changed with several values while the other variables have been left with the same values as in the preliminary simulation.

Table 8: The new values used in the price scenarios

Variables	Unit	Range of values
Price of bought energy	€/kWh	0,02; 0,06; 0,1; 0,14; 0,18; 0,22; 0,26; 0,3
Price of sold energy	€/kWh	0; 0,01; 0,03; 0,05; 0,07; 0,09; 0,11; 0,13
Price of the PV system	€/kWp	1.600; 1.300; 1.000; 700; 400
Price of the storage	€/ kWh_c	1100; 900; 700; 500; 300

3.3 Solar PV in crop drying

3.3.1 Kustavin Agri

“Kustavin Agri” is a cooperative of crop producers that share a grain dryer among five partners. The dryer is located in the municipality of Kustavi, in the South-Western region Varsinais-Suomi, and it has been operating since 2017. Close to the dryer, a power plant produces heat by burning wood chips and sends hot water to the buildings in the town for the heating needs. The same district heating unit is used to obtain heat energy for the crop dryer, making use of the heater when the energy needs of the town are yet relatively low at the end of the summer.

The dryer receives hot water at around 95º C and circulates it through a heat exchanger that transfers the heat to the air with the help of a fan. The air is usually heated to around 85º C for drying the grain, but sometimes 60 or 70º C are sufficient for drying, for example, peas or horse beans. The same temperature could be used to dry the grain as well, but that would require longer drying times than when using higher temperatures. Two radiators with capacities of 500 kW each are used as heat exchangers, and each of them have two fans that blow the air from the outside into the dryer through them. That is, the dryer has an installed capacity of 1 MW in total, but the radiators are used in alternation and they are never used simultaneously. Therefore, the dryer has a heating capacity of around 480 kW, and normally it consumes below 400 kW.

The electricity is taken from the grid and is used for all the electric devices of the dryer such as elevators, ventilators and feeders, with a total electric installed capacity of 60 kW. As the dryer is virtually used only during the drying period, the electricity consumption as well at the heat consumption are insignificant at other times of the year. Therefore, other energy consumptions have not been considered in this case, and the analysis focuses only on the energy use during the drying period. Besides, as this section addresses the heating needs of crop dry, the electricity consumption has not been taken into account.

The data of the energy consumption has been obtained from the bookkeeping of the dryer that is carried out by the users. There, information is provided about the weight, the moisture level, the time and the energy before and after each batch, and thus the energy that, for instance, takes to dry a ton of crop or to evaporate a kilogram of water has been possible to calculate.

3.3.2 Consumption

The dryer has been installed recently and data of the energy consumption is available only for the years 2017 and 2018. As mentioned in the previous case, the year 2018 was very dry and the amount of produced crops was below normal level, thus the energy consumed by the dryer also was lower than usually. Not only is lower the total consumption of the drying period, but the energy required to dry the same amount of crop also is lower with such weather conditions. Therefore, it has to be taken into account that the available data is quite limited and may not represent the most common values of crop dry. However, in this case the data is enough to estimate roughly the suitability of solar energy with the heating needs of crop drying.

As stated previously, the dryer has a heating capacity of 480 kW, but its full power is used rarely and usually the consumption is below 400 kW. Based on the obtained data, the dryer consumes on average 300 kW, but significant differences can be seen from one year to the other as in 2017 the average was 350 kW, and in 2018 it was 256 kW. Table 9 displays average values of the consumed energy for both years.

Table 9: Average values of the energy consumption in the dryer in 2017 and 2018

Average values	**2017**	**2018**
Power (kW)	351	256
Energy per dried ton of crop (kWh/dried ton)	192	156
Energy per evaporated kilogram of moisture (kWh/kg of H_20)	1,7	1,5
Energy per batch (kWh)	3.800	1.800
Daily consumption (kWh)	6.150	1.900
Monthly consumption (kWh)	143.000	21.100
Total consumption (kWh)	159.800	32.500

3.3.3 Solar production

The solar photovoltaic production has been estimated using the same procedure as in the previous case explained in Section 3.2. That is, the production data has been obtained using the online tool PVGIS (European Commission 2017), and the location of the dryer has been set as the location for the solar data shown in Figure 30. The same way, the slope has been chosen to be 45º and the azimuth 0º. The type of PV panel has been set crystalline silicon, with system losses of 14 % and an installed capacity of 1 kWp. The solar PV production values have been calculated for the period of 10 years from 2006 to 2015.

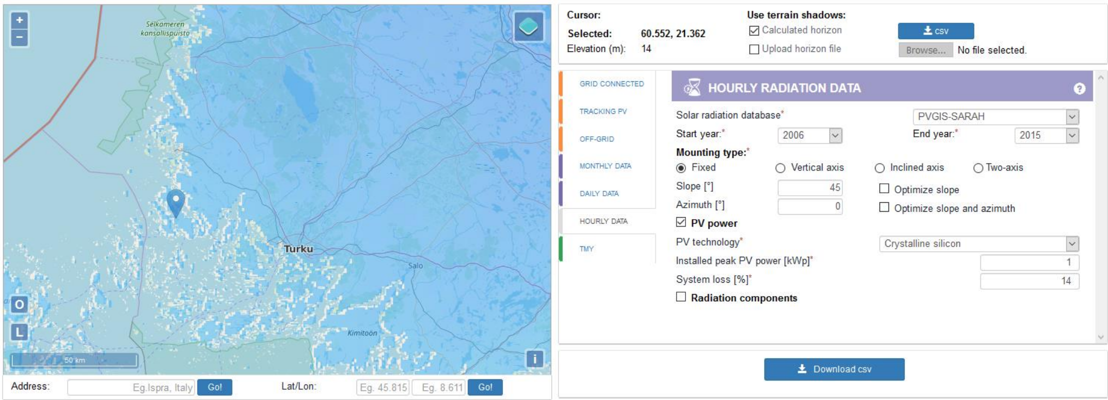

Figure 30: The location and the specifications of the PV system (European Commision 2017)

Based on the production data of the online tool, a daily solar PV production of 2,8 kWh/kWp has been estimated as the average on the drying period, and a monthly value of 84 kWh/kWp. However, as the solar irradiation decreases during the drying period, the same way is the produced energy lower in October than in August, and the average production shows a decreasing tendency among the period as Figure 31 shows. At this point, it is important to remember that the aim of this section is not to make a numerical analysis of the situation; it rather intends to speculate about the potential of solar PV energy in the drying.

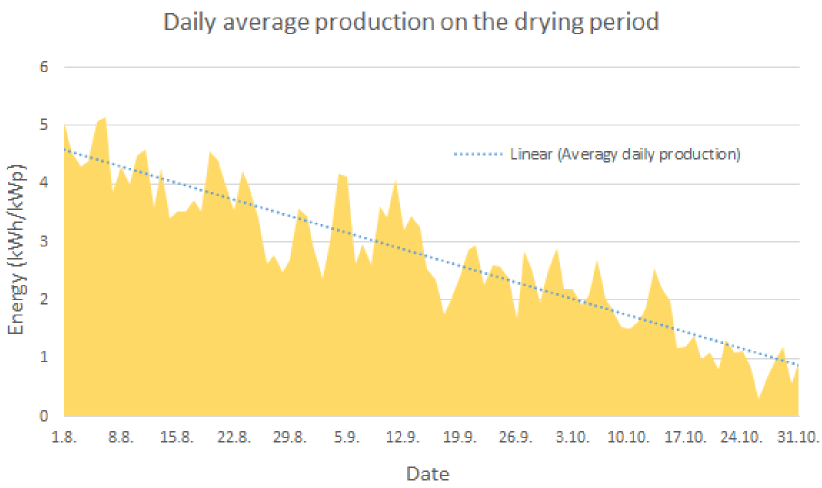

Figure 31: Average daily PV production during the drying period

After estimating the amount of solar energy that could be produced per installed kilowatt peak, it has been compared to the energy consumption of the dryer. In this case, same as in Section 3.1, the production and consumption do not match on their form of energy; that is, one is in the form of electricity while the other is in the form of heat energy. Hence, the use of heat pumps has been contemplated as a possibility of transforming the electricity into heat, and their possible uses have been discussed in the context of crop drying and solar PV energy.

3.3.4 Heat pumps

Heat pumps are already well-known devices that increase the energy quality of a fluid by consuming electricity. That is, they absorb heat from a source with low temperature and convert it into heat with higher temperature that can be transferred to the same or another fluid. For that, they need electricity to operate inner components that are responsible for the process of increasing the quality of the fluid. The main components are the evaporator, the compressor, the condenser and the expansion device, and the heat absorbed by the evaporator is improved and provided as useful heat by the condenser. The useful heat provided by heat pumps depends largely on the quality of the heat in the source, thus the performance of the device improves with a higher absorbed temperature. As the source from where the heat is extracted is considered an infinite source of energy, the efficiency of heat pumps is defined by their output heat energy (Q_h) and their input electric energy (W_e), and is denoted as the coefficient of performance (COP), defined as follows (12):

$$COP = \frac{Q_h}{W_e} \tag{12}$$

The use of heat pumps has significantly increased in the last years, especially as space heaters, and there is a wide variety of heat pumps for several purposes. They are best known for their multiple uses at indoors, such as homes and offices, as the same device can be used for air heating, cooling and ventilation. Besides, they can be used as water heaters for swimming pools or the district heating, for example, and they can serve as heat or cold producers for industrial purposes. Their wide range of uses comes from their ability of providing energy with different temperature levels upon the needs. Further, they also are widely used because they can absorb the heat from several sources such as the ambient air, a body of water and waste fluids from other processes.

Conventional heat pumps usually operate at source temperatures that are defined by climatologic conditions. In the case of the air-source heat pumps, the heat can be absorbed from sources that are below zero. In the cases where the source is a body of water or the ground, temperatures never go below the freezing point and a similar source temperature is assured throughout the year (Staffel et al. 2012). When waste fluids are used as the source, the heat can be harvested at temperatures as high as 40° C or even more. When it comes to the useful heat, conventional heat pumps with natural sources provide temperatures high enough for space heating and can reach temperatures up to 60° C. As the source temperature increases, their capacity of providing higher temperatures is improved; industrial heat pumps, for example, can reach temperatures of 100° C. Higher temperatures than 100° C can be obtained by the high temperature heat pumps (HTHP), and they are mainly used for heat recovering or upgrading with industrial purposes when sufficiently high source temperatures are available.

The COP of high temperature heat pumps range between 2,4 and 5,8 for increased temperatures of 95° C and 40° C consecutively, with heating capacities that begin from 20 kW to as high as 20 MW (Arpagaus et al. 2018). In the case of the conventional heat pumps, temperature differences of around 60° C can be obtained usually with a COP of 2 while for a COP of 5 the temperature increase remains close to 20° C (Staffel et al. 2012). Their heating capacities range from few kilowatts, in the case of domestic use, to tens or even a few hundred kilowatts for swimming pools or commercial purposes. Industrial heat pumps usually have capacities of around 1MW, but there are cases with capacities of up to 50 MW (Luoranen 2017).

4 RESULTS AND DISCUSSION

Chapter 3 has explained the materials and methods used in the thesis, and this chapter presents the results obtained from that process. Following the same order, this chapter is divided into three parts that cover the three sections of the previous chapter. That is, Section 4.1 introduces the results from Section 3.1 with regard to the general numbers in Finland, and discusses the main outcomes. Section 4.2 presents the results that correspond to Section 3.2, and discusses them. Here, the part of solar photovoltaic and the electricity use in crop drying is covered, based on one of the reference cases as well as contemplating the future of the technology and prices. Section 4.3, based on the second real case, displays the results related to Section 3.3 and focuses on the discussion about the solar photovoltaic energy and heating needs of crop drying.

4.1 Crop drying and solar energy in Finland

In Section 3.1, it has been estimated that around 600 GWh of heat are used on average every year in Finland to dry the crop. When it comes to the solar production, the monthly photovoltaic energy than can be produced in a square meter has been estimated at 14,36 kWh for the drying period. Besides, the available rooftop area for the solar electricity production in a typical farm has been assumed at 500 m².

Comparing the needs with what is available, the results show that almost 4.200 ha of solar PV panels would be needed in total in order to cover the annual energy consumption of crop dry in Finland. Taking into account that close to 35.000 farms produce crops in the country, covering crop dry with solar energy would entail an area of 0,12 ha or 1.200 m² per each farm producing crops. In terms of the installed PV power, close to 200 kWp would be needed per farm. On the other hand, considering the total rooftop area of the buildings out of urban areas in Finland, and assuming that 50 % of it could be available for solar production, it could be said as a rough estimation that a fifth part of that area would cover the energy consumption of crop dry. Besides, with the same logic, the estimated available area of rural residential buildings would be enough to cover the same energy consumption.

It is important to take into account that those comparisons ignore the temporal and qualitative characteristics of the energy. That is, on the one side the estimated energy consumption refers to heat energy while the estimated solar production refers to the electricity. Therefore, those comparisons assume that the crop would be dried directly with electricity, a method that is not used in reality. However, heat pumps could convert the electricity into heat, and in addition, increase the energy capacity two or even four times. That would mean a significant reduction in the PV area ―between two and four times less surface would be needed.

On the other side, temporal characteristics of the solar energy have not been considered on the comparisons. In other words, it has been assumed that the production and consumption would occur simultaneously, or that the excess production could be used later when needed. That would require a storage system able to save the energy at certain moments and to provide that energy at other moments. This matter will be addressed further in Section 4.2.

When it comes to the electricity consumption of crop drying in Finland, no data or information has been found at the Finnish level. Nevertheless, as mentioned in the literature review, it is estimated that the electricity consumption of crop dry process is around 10 % of the fuel consumption. In this way, it has been assumed that the total electricity consumption is on average 60 GWh. Considering that 35.000 farms produce crops in Finland, an area of 120 m² of solar panels per farm would be sufficient to cover the electric needs of the drying, an equivalent of 20 installed kilowatts.

In the case of the available rooftop area in the farms, as already mentioned, it has been estimated that around 500 m² could be used in farms that produce crops. Comparing to the 120 m² needed to cover the electric needs, and being aware of the assumptions mentioned above, it could be said that there is sufficient space in the roofs of crop producing farms to cover all the electricity consumed by the dryers. Moreover, in terms of the amount of energy, it could be said that almost half of the heat used in the process could be covered with the solar energy using the current available rooftops. It is important to consider that those numbers are just rough estimations of the current situation and not accurate numbers for technical purposes. Hence, their intention is to give an idea about the solar potential and its contribution to agriculture, in this case to the sector of crop dry.

4.2 Solar PV and electricity in crop dry

4.2.1 Results of the energy

The level of autonomy of the farm and the dryer is determined by the amount of energy that is imported from outside or, in the same way, by the energy produced and consumed locally. Therefore, the percentage of the consumed energy that could be covered by the solar production has been calculated. The results for the case were the total consumption has been considered are displayed in Table 10, while the results for the case where only the consumption of the dryer has been considered are displayed in Table 11.

Table 10: Consumption of the farm covered with solar energy

Covered consumption with PV (%)						
Farm		**Capacity of the storage** (kWh$_c$)				
		0	**50**	**100**	**150**	**300**
Installed PV power (kWp)	**0**	-	-	-	-	-
	30	23	37	41	42	43
	50	27	46	51	52	54
	100	32	54	61	64	68
	150	34	58	66	69	75

Table 11: Consumption of the dryer covered with solar energy

Covered consumption with PV (%)						
Dryer		**Capacity of the storage (kWh)**				
		0	**50**	**100**	**150**	**300**
Installed PV power (kWp)	**0**	0	-	-	-	-
	30	15	29	34	36	39
	50	21	37	45	48	52
	100	28	46	56	64	75
	150	32	50	61	70	85

Not surprisingly, the energetic autonomy of the farm increases when the capacity of the energy production system is increased. That is, a larger PV installation as well as a larger storage capacity increase the share of solar energy, decreasing the need to import energy from the outside. However, the share of solar energy develops differently depending on whether a larger PV system or a larger storage capacity is chosen. That can be seen in Table 10, where increasing the size of the PV system has a larger impact in the share of solar energy than the increase of the storage capacity. For example, with a system of 50 kWp and 50 kWh$_c$ and doubling the storage capacity to 100 kWh$_c$, the share increases five percentage points, while doubling the PV capacity increases the share eight points. However, the difference is not very big and attention has to be put to the fact that the comparison is based on different units, thus the dimensions are different. Therefore, such comparisons are more complete when other aspects of the system such as the self-used energy or the investment cost are considered, and that will be done later in this section.

At this point, it is interesting to look at the share of solar energy in the electricity consumption, and to compare how it changes depending on which energy uses are taken into account. That can be seen when the solar share is compared between the cases where the consumption of the whole farm and the consumption of only the dryer are considered. A smaller production system is proportionally more beneficial for the case where the farm is considered, but a larger system has a higher impact if only the dryer is taken into account, as Table 11 shows. There, the share of the solar energy is lower than in Table 10 for most of the cases, but becomes larger for the cases with installed capacities of over 100 kWp of PV and 150 kWh of storage, with an increasing difference as the capacity of the system grows. In other words, larger PV and battery systems increase the share of solar energy with more percentage points when only the consumption of the dryer is considered, compared to when the whole farm is taken into account.

Another important aspect to consider in solar installations is the self-used or own-used energy; that is, the amount of energy that is consumed compared to the amount of energy produced. In cases without storage system, the consumption and production occur simultaneously and the rest of the energy, what is not consumed, is sold to the grid. In the case where batteries are used, the consumption does not have to occur necessarily at the same time as the production, and the energy can be stored and consumed later. Storing the energy improves significantly the rate of self-used energy, as can be seen in Tables 12 and 13.

Table 12: Percentages of the solar energy use in the farm

Self-used solar energy (%)						
Farm		**Capacity of the storage (kWh)**				
		0	**50**	**100**	**150**	**300**
Installed PV power (kWp)	**0**	-	-	-	-	
	30	48	79	86	88	91
	50	34	58	64	67	69
	100	20	35	39	40	43
	150	15	25	28	29	32

Table 13: Percentages of the solar energy use in the dryer

Self-used solar energy (%)						
Dryer		**Capacity of the storage (kWh)**				
		0	**50**	**100**	**150**	**300**
Installed PV power (kWp)	**0**	-	-	-	-	-
	30	6	12	14	15	16
	50	5	9	11	12	13
	100	4	6	7	8	9
	150	3	4	5	6	7

In this case, it is much more significant whether other energy consumptions are taken into account or not. If considering other energy uses affects positively to the percentages of covered energy, in the case of the self-used rates the difference is much larger. The former comparison has shown that the energy coverage may vary differently depending on the size of the production system. For the rates of own-used energy, instead, the increment on the percentage is much more significant when other energy consumptions are included. There, it has to be taken into account that the energy use of the dryer occurs mainly —or only— during two or three months and that the energy is produced throughout the whole year. Therefore, the rate of self-used solar energy in an annual basis is very low for the use in the dryer, and much bigger for the whole farm. In both cases, the implication of the storage is what attracts most attention, especially for the lowest installed capacities of the solar energy.

4.2.2 Economic results

It has been seen that significant levels of autonomy or self-use rates can be reached with different combinations of solar panels and the battery storage. The 85 % of the electricity consumed in the dryer could be produced locally, and 91 % of the solar production could be used for the own energy consumption. However, other aspects need to be taken into account in order to make a more complete analysis of the situation. Therefore, the results of the calculated net present value and discounted payback period are given in this section. As mentioned earlier, the NPV of each combination —solar panels and battery storage— has been calculated in relation to the reference case, thus those results are in relation to the case where no PV nor storage system is considered.

Net present value

Table 14 displays the net present value of each combination for the calculations where all the energy consumed in the farm has been considered, and Table 15 shows the values for the energy used only in the dryer. Here, different conclusions can be made comparing to the results above. While previously larger storage capacities have given better results in general, large sizes of PV give better results in this case, and the implication of the storage is significantly lower. That might be caused by the relatively high price of the batteries, as the price of 900 € per installed kilowatt hour of storage capacity has been assumed for this simulation. However, compared to the investment costs of the different sizes of the PV system, the storage does not suppose extremely higher expenses.

Table 14: Net present values of the different cases in relation to the default case

NPV (€)						
Farm		**Capacity of the storage (kWh)**				
		0	**50**	**100**	**150**	**300**
Installed PV power (kWp)	**0**	0	-	-	-	-
	30	20.542,48	6.703,07	-17.396,67	-43.446,22	-123.080,12
	50	24.562,83	14.115,28	-8.397,28	-33.695,19	-113.322,09
	100	29.224,60	22.255,66	1.002,94	-23.285,09	-100.629,54
	150	31.653,71	26.139,36	5.528,41	-18.272,41	-94.136,96

Table 15: Net present values when considering only consumption in the dryer

NPV (€)						
Dryer		**Capacity of the storage (kWh)**				
		0	**50**	**100**	**150**	**300**
Installed PV power (kWp)	**0**	0	-	-	-	-
	30	2.810,11	-21.787,12	-47.884,35	-74.539,63	-155.303,62
	50	3.979,92	-20.255,80	-45.981,86	-72.385,44	-152.914,69
	100	5.450,21	-18.534,57	-43.692,23	-69.458,95	-148.687,35
	150	6.317,64	-17.557,04	-42.561,34	-68.176,36	-146.618,21

At first sight, one may think that even with relatively small PV systems —30 or 50 kWp in this case—, a large storage capacity —150 kWh for example— could improve the whole system as seen in Table 12, since the rate of self-used solar energy would be increased and thus the energy import from the grid decreased. However, in order to store sufficient energy in the batteries, the small PV system would need several hours of sun without any consumption happening at the same time. That is rare to happen because, in fact, crops are dried on sunny days, meaning that during the drying period most of the produced energy is consumed simultaneously and lacks of opportunity to store the energy. A larger PV system would be needed in order to ensure enough energy to store, supposing a larger investment cost that, together with a large storage system, would make the investment to be excessively expensive.

Thus, looking at the economic side gives a different understanding of the concern addressed previously. Although a combination of large PV and storage sizes can be energetically optimum, Tables 14 and 15 express opposite economic results. In this case, the worst results come from the combinations that previously demonstrated the best ones. That is, a small PV system together with a large storage capacity offer the largest self-use rate, and a large PV system together with a large storage capacity have the largest share of solar energy in the consumption, but both are among the economically most negative combinations.

One important conclusion drawn from there is that the value of energy is not sufficiently high to make such production systems economically viable. That is because the energy cost avoided by consuming own energy and importing less does not compensate the capital expenditure of the production system, and a higher energy cost or a lower investment cost are needed in order to improve the economic viability of the system. That speaks a lot about the importance of the energy price when it comes to renewable energy installations in general, where high costs of energy may create better conditions.

Another conclusion is that adding more capacity storage than the installed PV power makes the system to be economically obsolete when the consumption of the whole farm is considered. Furthermore, if the energy production system is designed only for the use in the dryer, any size of the storage makes the system to be economically negative, as Table 15 shows. Relating to the mentioned earlier, the reason behind that is that the storage does not compensate in such energy-intensive activities where large amounts of energy are consumed in relatively short periods, and where the production is not temporally sufficient for the consumption. Nevertheless, adding storage capacity makes the most sense for the largest PV sizes as seen in Tables 14 and 15. In other words, increasing the installed power of the PV system makes more convenient —or less negative— to increase the storage, while higher values of the covering and self-using rates are obtained. For example, it can be seen in Table 14 that the difference between excluding the storage and using a 50 kWh_c storage is larger for the PV system of 30 kWp than for the PV system of 150 kWp. In both cases, the NPV decreases with the use of the storage, but for the larger PV system the decrease of the value is smaller, besides increasing the covering and self-using rates.

Finishing with the results of the net present value, it has been found that albeit without the support for the investment, the PV system of 30 kWp —without the storage— shows a better economic viability than not having any PV system. That occurs when the consumption of the farm is included in the simulation, as Table 16 shows, while installing solar panels without the support and only for the energy use in the dryer is not economically convenient for any of the cases. Again, that demonstrates that the energetic outcomes —covering and self-using rates— of the production system do not necessarily match with economic ones, at least with current economic conditions. There, as already mentioned before, it is important to remember that the economic variables used in the simulation are calculated and estimated based on recent market conditions that, year after year are becoming more favourable for the renewable production systems.

Table 16: Net present values without the support

NPV without support (€)						
Farm		Capacity of the storage (kWh)				
		0	50	100	150	300
Installed PV power (kWp)	0	0	-	-	-	-
	30	4.942,48	-26.896,93	-68.996,67	-113 046,22	-246.680,12
	50	-1.437,17	-29.884,72	-70.397,28	-113.695,19	-247.322,09
	100	-22.775,40	-47.744,34	-86.997,06	-129.285,09	-260.629,54
	150	-46.346,29	-69.860,64	-108.471,59	-150.272,41	-280.136,96

Discounted payback period

The next part of the simulation has been the calculation of the discounted payback period, which leads to the last set of results. Besides telling about the amount of years that each installation needs for paying itself back, the payback period also facilitates an easier comparison among the different cases than doing it with the net present values. Logically, the results of the discounted payback period correlate with the net present values, but as mentioned, the relation among different cases is easier to identify and evaluate in this case. Thus, the main results of the discounted payback periods are displayed in Tables 17 and 18. Similarly to the NPV, the best result that in this case is the lowest payback period, comes from the case with the installed PV capacity of 30 kWp and with no use of the battery storage. An estimated period of 12 years would need such installation to pay itself back if the energy consumption of the farm is considered; if only the energy consumption of the dryer is used, almost the double of time would be needed, 22 years.

Table 17: Discounted payback periods if the whole farm is considered

Discounted Payback period (years)						
Farm		Capacity of the storage (kWh)				
		0	50	100	150	300
Installed PV power (kWp)	0	-	-	-	-	-
	30	12	22	36	56	70
	50	14	20	29	40	70
	100	17	20	25	31	57
	150	19	21	24	29	45

Table 18: Discounted payback periods when considering only the dryer

Discounted Payback period (years)						
Dryer		Capacity of the storage (kWh)				
		0	50	100	150	300
Installed PV power (kWp)	0	-	-	-	-	-
	30	22	59	70	70	70
	50	23	42	70	70	70
	100	23	33	45	60	70
	150	24	30	38	46	70

Exactly the same way as previously, the simplest combination shows a positive result, even in the scenario without any support for the investment. As Table 19 shows, the installation with 30 kWp and no storage would pay itself back without any support after 22 years, if compared to the reference case. Taking into consideration that the lifetime of the system has been estimated at 25 years, the result may be seen as not very attractive. However, as the market prices become more favourable by increasing the energy price or decreasing the investment costs, the calculated payback period of 22 years can reduce significantly.

Table 19: Discounted payback periods without the support

Discounted Payback period without support (years)						
Farm		Capacity of the storage (kWh)				
		0	50	100	150	300
Installed PV power (kWp)	0	-	-	-	-	-
	30	22	44	70	70	70
	50	26	39	64	70	70
	100	33	39	53	70	70
	150	37	41	51	64	70

At this point, and going to the real case of Kasken tila, it is interesting to mention that for the actual PV system of 30 kWp, a payback period of 10 years was estimated when the installation was made in 2017. In practice, however, that period seems to be shortening as was informed by the farmer. In this study, it has been theoretically calculated in the simulation that a PV system with the same size would pay itself back after 12 years. However, it has to be taken into account that in this case a discounted payback period has been calculated and that a normal payback period gives a result of 10 years. Further, the simulation assumed a slope of 45°, while the actual solar panels in the farm are installed with different slopes.

Thus, it can be said on one side, that the simulation-based calculation done in this work correlates quite accurately with the real case. On the other side, it can be said that in practice results may be better than the theoretical estimations. About the latter one, it is important to state that the estimated variables have not been chosen to be optimal ones but rather to represent average values, in order to estimate a common case and not a case-specific technical solution. Therefore, it is important to take into account that the results obtained in this study represent an average situation of the solar photovoltaic in the context of the grain drying, and that the situation will improve, as external conditions become better.

<u>Price scenarios</u>

The importance energy prices have on the viability of solar photovoltaic systems has been highlighted several times. It has been stated that a higher price of the bought energy improves the viability of the system that produces energy locally, and the same happens when the price of the energy that is sold to the grid is increased. Logically, the contrary occurs when the prices of the PV and battery systems are increased, as the investment costs become larger. In order to understand better the relation of each economic variable with the viability of the system and with each combination, different price scenarios has been simulated. That is, the values of the economic variables have been changed in the simulations.

Thus, future scenarios have been simulated, estimating the effect that each price variation would make in the discounted payback period of the PV and battery system. Results are shown for the installed PV capacities of 30 and 100 kWp, in combination with all different storage capacities used previously. The results of the discounted payback periods develop differently depending on the size of the system, and that is the reason of choosing two different sizes of the PV capacity. Here, only the consumption of the whole farm has been considered, and the support for the investment has been included in all the combinations of PV and battery systems.

Figures 32 and 33 illustrate the relation of the discounted payback period with the price of the energy that is imported from the grid. As mentioned earlier, the electricity price is expected to rise in the future, following its tendency of the last two decades. The electrification of the energy and transportation systems, together with other conditions, can significantly increase the demand of electric energy, causing electricity prices to rise. Therefore, a scenario with an increase of the energy price up to 200 % has been contemplated. However, the opposite situation has been considered too, where the price of the electricity decreases to almost zero.

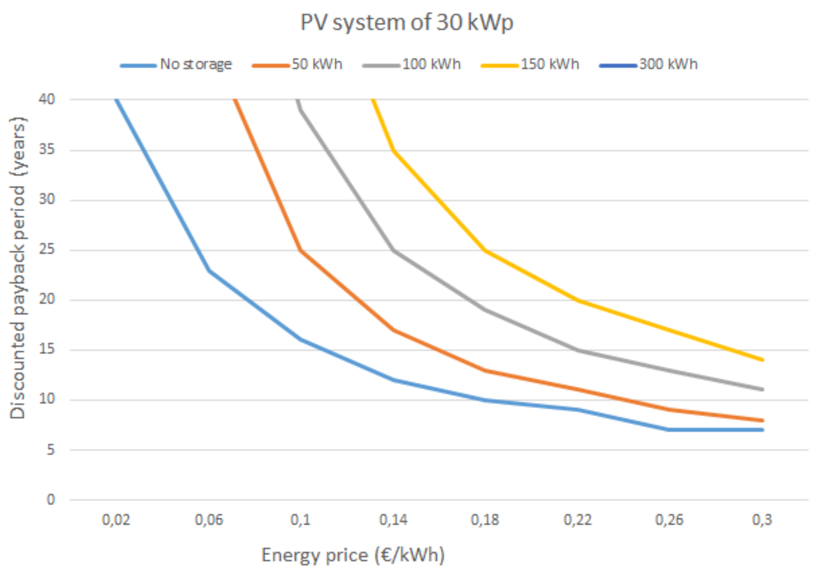

Figure 32: The discounted payback period against the price of bought energy, for the 30 kWp PV system and for each storage capacity

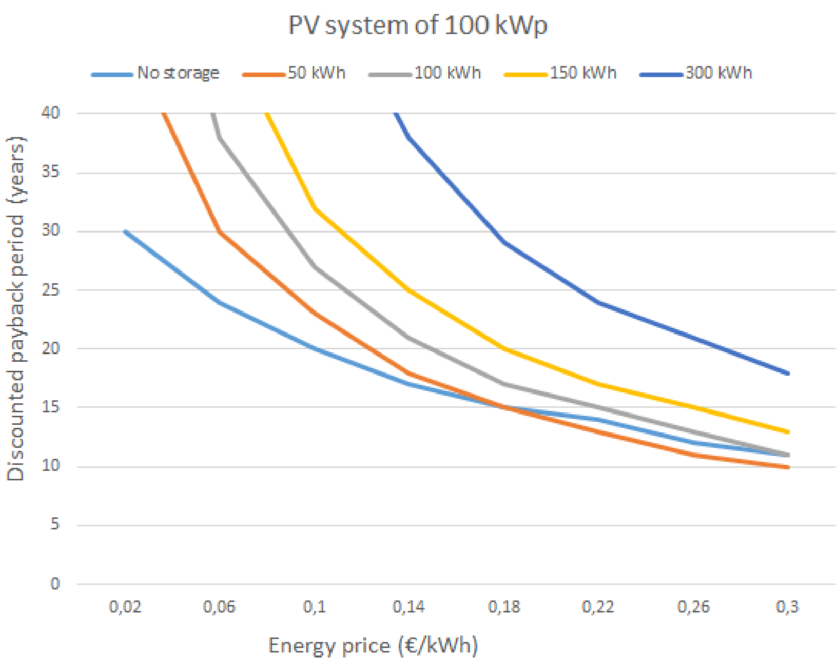

Figure 33: The discounted payback period against the price of bought energy, for the 100 kWp PV system and for each storage capacity

For the smallest PV system, illustrated in Figure 32, all the combinations of PV and storage show lower discounted paybacks than the lifetime of 25 years, when the energy price is higher than 0,18 €/kWh. Furthermore, excluding the storage would also make the larger PV system to be viable even in the case where the energy price of the imported energy halves from the current value of 0,14 €/kWh.

Similarly develops the discounted payback period with the change in the price of the energy sold to the grid. Figure 34 describes the case of the smallest PV system, where the period decreases almost linearly against the increase of the sold energy price, meaning that the price difference does not affect in excess. In larger systems, however, the change of the sold energy price affects more as it can be seen in Figure 35, especially when the price goes towards zero. There, all PV and storage combinations become economically viable when 0,08 euros per kilowatt hour or more is paid for the sold electricity. In these scenarios, it is worth mentioning that the PV system of 30 kWp, without storage or with a storage capacity of 50 kWh_c, would not require any revenue for the excess energy in order to be more profitable than just importing energy from the grid.

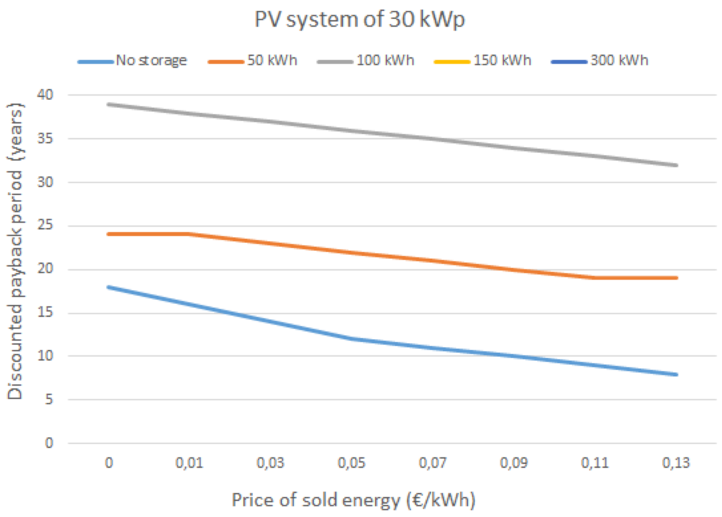

Figure 34: The discounted payback period against the price of sold energy, for the 30 kWp PV system and for each storage capacity

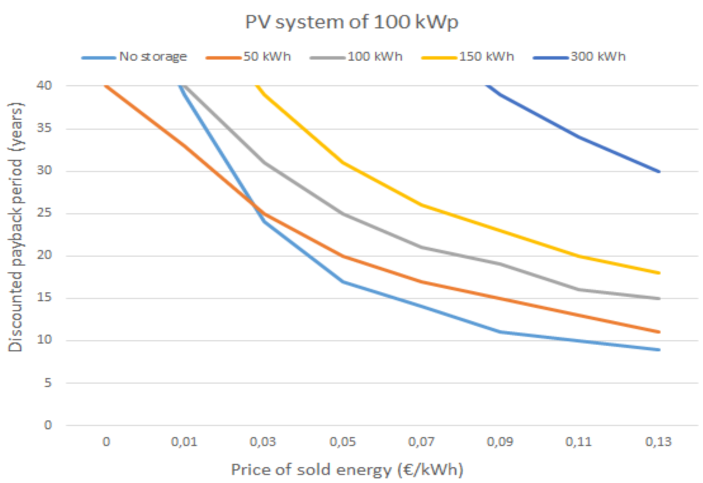

Figure 35: The discounted payback period against the price of sold energy, for the 100 kWp PV system and for each storage capacity

When it comes to the scenarios where prices of the installation are considered, the reduction of both the PV and storage prices cause the payback period to be lower. Unlike the energy price variations, the changes in the investment cost affect proportionally to the number of years needed for the system to pay itself back. That is seen in the following graphs, where price scenarios of the PV system and the battery storage system are illustrated.

Figures 36 and 37 represent price scenarios of the capital cost of the solar PV system. In both PV sizes, it can be observed that without the storage or with a relatively small storage, the use of solar energy gives positive results despite price variations of the PV system. In any of the cases, however, the use of the largest storage capacities would make the system to be unprofitable, especially the storage capacity of 300 kWh. Independently of the storage size, the same decrease in the price of the PV system would influence more to the larger PV sizes, as it can be seen when the steepness in Figure 37 is compared to Figure 36.

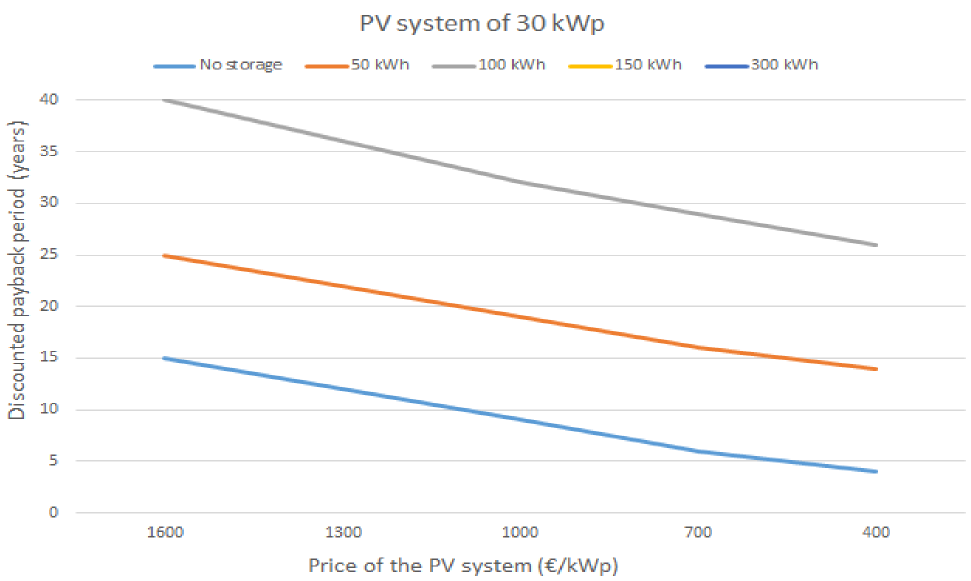

Figure 36: The discounted payback period against the price of the PV system, for the 30 kWp PV system and for each storage capacity

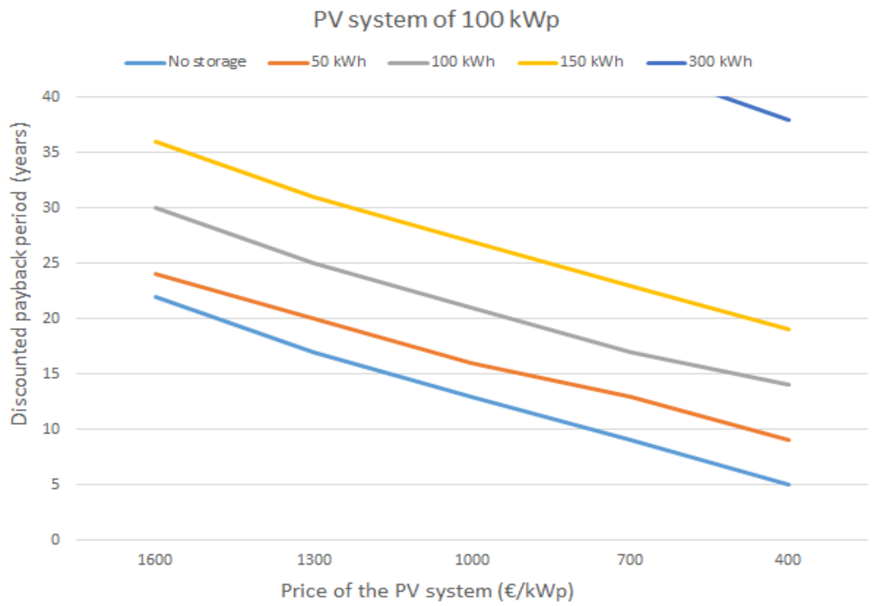

Figure 37: The discounted payback period against the price of the PV system, for the 100 kWp PV system and for each storage capacity

In the last case, where the effect of the storage price variation in described, a different tendency can be identified. Here, as Figures 38 and 39 show, the viability of the system is very low for the combinations with large storages when storage prices are high, but relatively good for combinations with smaller storage capacities. Nevertheless, all the combinations have the discounted payback period of less than 25 years when the price of the storage becomes three times cheaper than the current assumed price of 900 €/kWh. For the case of the storage capacity of 300 kWh, 300 € per installed kilowatt hour is the maximum price for the system to be economically positive, as can be seen in Figure 39.

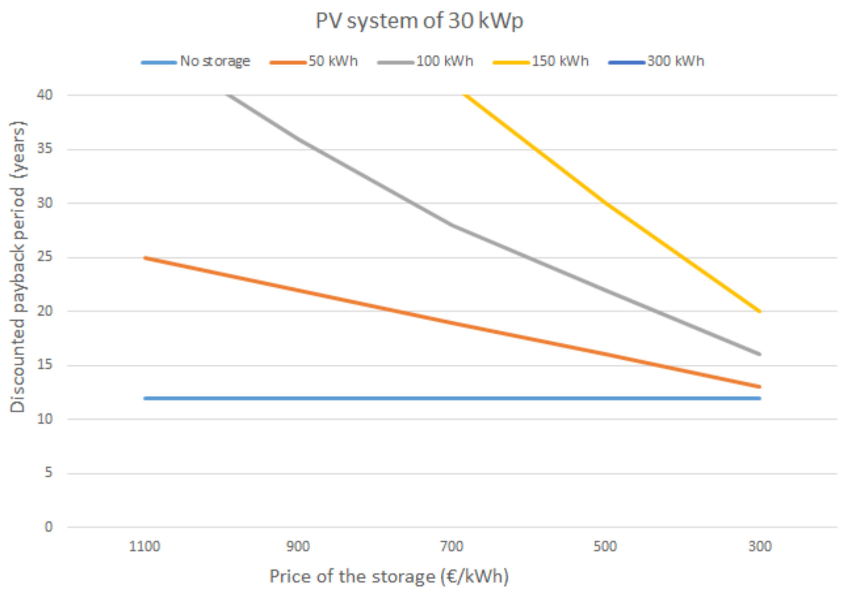

Figure 38: The discounted payback period against the price of the battery system, for the 30 kWp PV system and for each storage capacity

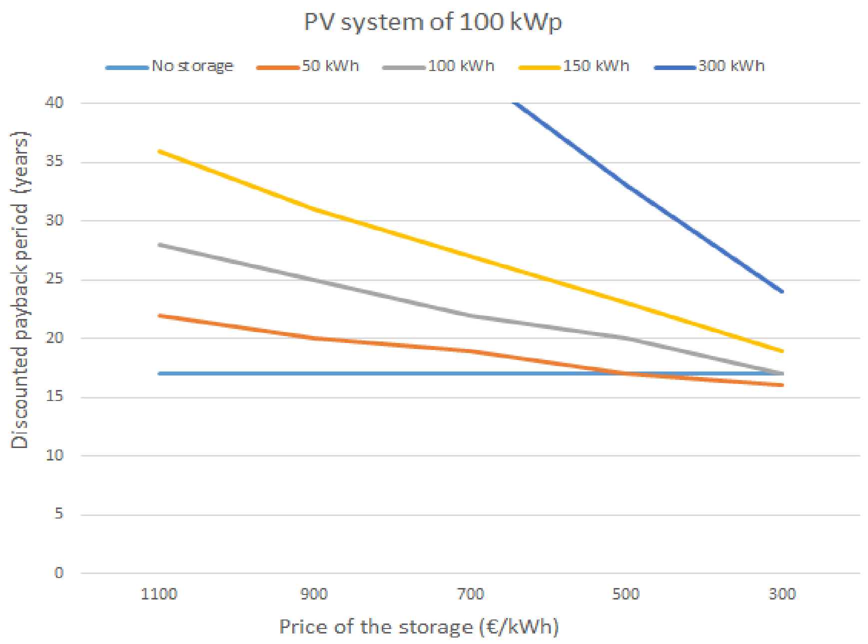

Figure 39: The discounted payback period against the price of the battery system, for the 100 kWp PV system and for each storage capacity

After looking at the results in the previous graphs, it can be deduced that the profitability of the system is more sensible to variations of the storage price than to variations of the price of the PV system. Where the change of the PV price impacts equally to all combinations with different storage capacities, the change of the battery price affects significantly more to the larger installed capacities than the smallest ones used in the simulation.

Among different sizes of the PV system, 30 and 100 kWp in this case, most important differences can be seen in the viability of the storage. The adoption of large storage does not make very much sense for the smallest PV size, as seen in Figures 36 and 38, whereas Figures 37 and 39 demonstrate that using larger storage can be economically positive, especially with lower PV or battery prices. However, as mentioned earlier, using larger storage capacities than their equivalent PV capacities does not usually give good results to the system.

Similar happens with the energy price variations where largest storage capacities are not worthy for the smallest PV capacities used in this work, despite significant increases of the prices. When it comes to larger PV sizes, even the largest storage system can be economically viable if energy prices are high enough, and they are more sensible to variations in the price of the imported energy than to the price of sold energy as can be observed comparing Figures 33 and 35.

In conclusion, it has been seen that the smallest sizes of PV systems are economically more viable than the larger systems for such energy uses, even if the covered and self-used rates of energy are lower. Besides, using large PV systems rather than large storage systems has been found to be better in most of the cases, and the latter ones are worth use if large PV systems are installed. That combination, however, implies very high investment costs that are far from being economically viable with current prices, but future scenarios may be positive as installation costs decrease and energy prices possibly increase. Logically, cheapening the prices of PV installations would be beneficial for large PV systems as well as cheapening battery prices would help large storage systems to be more accessible. The expected decrease of both PV and battery prices, therefore, could boost large solar energy production systems in favour of the local and distributed energy generation.

4.3 Solar PV in crop drying

In Section 3.3.3, it has been estimated that, on average, 2,8 kWh of electricity are produced by an installed PV capacity of 1 kWp in a day during the drying period, and 84 kWh in a month. Considering the consumption levels calculated in Section 3.3.2 and displayed in Table 9, it has been estimated that the energy consumed to dry a ton of crop equals to the energy produced by a PV system of 68 kWp in a day, for the case of the consumption levels of 2017. For the consumption values of 2018, the energy produced by a 55 kWp PV system in a day could cover the energy consumed to dry a ton of crop. Those estimations are, as mentioned, assuming the direct heating with electricity, and their only purpose is to compare the energetic dimensions of crop dry and solar energy. It is obvious that only solar PV energy lays far from being able to cover the drying needs.

Therefore, the use of the heat pump has been considered together with the solar energy, with the intention of contemplating the potential they could offer. In this case, the theoretical production system includes an installed PV capacity of 200 kWp and a heat pump with an assumed COP of 4. The estimated production of the system is illustrated in Figures 40 and 41, together with the energy consumed in 2017 and 2018, respectively.

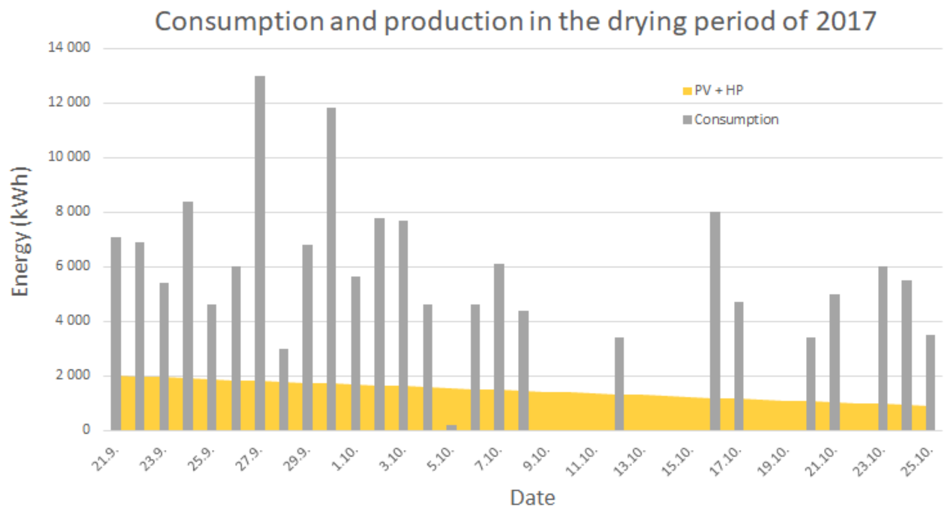

Figure 40: The consumption of the dryer and the estimated production of the system (PV with 200 kWp and HP with a COP of 4), during the drying period of 2017

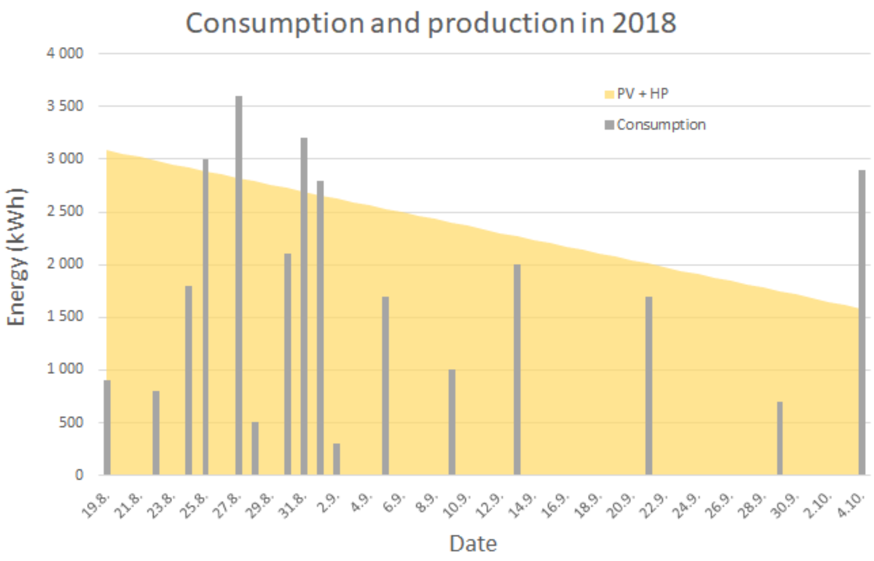

Figure 41: The consumption of the dryer and the estimated production of the system (PV with 200 kWp and HP with COP of 4), during the drying period of 2018

A clear difference can be observed from Figure 40 to Figure 41 in the covering capacity of the production system, caused by the low energy consumption of the year 2018 that has been explained previously. Therefore, considering values of 2017 may give a more realistic understanding about the gap between the solar energy and crop dry, even using a heat pump that can increase the produced energy four times. This comparison demonstrates that the use of the solar PV energy lays far from being able to provide all the energy needed in the grain drying. Besides, it has to be noted that the comparison has not taken into account temporal differences in the production and consumption of the energy, meaning that the lack of sun at night or cloudy days have been ignored. However, as mentioned earlier, the aim has not been to make a numerical analysis of the energy flow but rather a rough estimation of the amount of energy consumed and the possible solar production, with the aim of understanding better the implications of the solar energy.

Thus, it is obvious that the solar energy, even supported by a heat pump, does not have the capacity of providing sufficient energy for the heating needs of crop dry in the context of hot air drying and within reasonable PV sizes. Similarly to the case of the solar PV and electricity in crop dry, a full level of energetic autonomy of crop dry using photovoltaic energy would suppose sizes and costs of installations that may sound little realistic nowadays. However, solar energy already may have a significant potential of reducing the imported energy also for the heating needs of crop drying, similarly to the case in Section 4.2.

In this case, photovoltaics could bring energy savings by providing electricity to the heat pumps. That is, industrial heat pumps, for example, could do the same work that nowadays is done by the heaters or boilers that use fuels, but consuming electricity instead of fuels. Hence, the only imported energy would be the electricity consumed by the heat pump, thus the electricity purchased from the grid. There, the solar energy could have the potential of providing local and free electricity, bringing significant savings on the imported electric energy. In that way, the solar energy could decrease the need for purchasing electricity from the grid while the electrification of crop dry process would dramatically decrease the use of fuels in crop dry. In the Finnish level, where it has been estimated that on average 660 GWh of fuel are used annually for drying crops, the full electrification of crop dry would imply a reduction in the annual fuel oil use of about 66 millions of litres.

However, current conditions seem to be little favourable for the adoption of heat pumps as heat producers for dryers. On one side, the investment prices of heat pumps make the installations to be too expensive in comparison with current heaters and boilers. On the other side, the energy prices of fuels and electricity do not create sufficiently good conditions for heat pumps. Considering future price scenarios, a sufficient decrease of the electricity price could make the use of fuels to be obsolete, depending on how does the price of heat pumps develop. Instead, an increase of the electricity price would difficult the use of heat pumps as heat producers in the crop dryers, but would create better conditions for the solar energy as the source of electricity.

The viability of heat pumps for the drying, however, would largely depend on the development of the oil price, as it would affect positively or negatively to the current heating system. Besides, it has to be noted that the low price of wood chips already makes the heating to be cheaper with the biomass than with the oil, and its price will hardly increase in the future. Therefore, hot air dryers supported by bio-heaters seem to have a more promising future than the theoretical ones supported by heat pumps, unless the prices of energy and heat pumps change dramatically.

Another possible way of using solar photovoltaic energy in crop dry could be the use of dryers assisted by heat pumps. A combination of current heaters with heat pumps and solar photovoltaics could also bring significant fuel and electricity savings. In this case, the heat pump would not have the necessity of providing temperatures as high as 80 or 90º C because they would not be directly heating the grain. Instead, they could be used as pre-heaters for the inlet air of the dryer thus the heater would need to use less energy to reach the temperatures required to dry the grain. Therefore, less fuel would be used in the heater and significant energetic and economic savings could be reached. For this purpose, conventional heat pumps could possibly be sufficient instead of industrial ones, meaning that technology that is more accessible would be used with lower costs.

A HP-assisted dryer would suppose importing the fuel for the heater, but also importing electricity for the heat pump in addition to the electric devices involved in the drying. There, solar energy could contribute similarly as in the previous supposition by providing free electricity when the sun shines. It is important to remember that both the heat pump and the solar PV system could be used for other uses than the drying, and they could bring significant savings, as Section 4.2 has demonstrated with the solar photovoltaic and other energy uses in the farm. Another detail to take into account about the contribution of the solar energy is the pricing tariff of the purchased electricity. Some electricity tariffs include price discrimination depending on the time of the day, usually with higher prices during daytime and lower at nights. Considering that, the solar energy could cover a significant part of the electricity consumption when it is more expensive, and most of the consumed electricity —when needed— would be purchased with its lower price.

The efficiency of the entire heating system, in both of the previous suppositions, could be improved further by using the exhaust air of the dryer as the heat source for the heat pump. With a higher source temperature, the heat pump would be able to provide more heat to the dryer or it would consume less electricity. In the first case, a higher contribution to the inlet air of the dryer would improve the performance of the and decrease the use of fuel; in the second case, a lower electricity consumption would reduce energy costs in the case where electricity is imported from the grid. Regarding the recirculation, some studies have expressed that significant savings can be achieved by using the exhaust air as heat sources for heat pumps. In the case of a continuous cross-flow grain dryer, for example, fuel savings of 30 % could be achieved with the recirculation, while in the case of drying solid products the savings could be up to 50 % (Minea 2014, Dyck 2017). In addition, heat pumps not only can improve the temperature of the inlet air for drying, but they also can improve the quality of the air by their dehumidification characteristics (Patel & Kar 2012).

In brief, heat pumps could be a strategic technology for the partial or even full electrification of the grain drying process, bringing cheap or even free energy to the sector. That area promises good possibilities for decarbonizing agriculture, but it will not be addressed further as it remains out of the scope of the thesis. However, it is important to mention that further research is needed to deeper analyse technical and other aspects of heat pumps in this context. With a future perspective, although bio-heaters seem to have a more promising role on replacing fossil fuels in the sector, better economic conditions and further research may enable favourable conditions for the heat pumps and the solar energy to improve the agricultural sector as well as the energy sector with the production of cleaner, cheaper and local energy.

5 CONCLUSIONS

This thesis has analysed the potential of renewable energy sources in the context of the Finnish agriculture. More specifically, it has focused on the availability and suitability of solar photovoltaic energy in the context of the agricultural activity of crop drying. There, solar electricity has been analysed and discussed from two approaches to the energy use in crop dry. The first one, the main part of the thesis, has compared the solar PV production with the electricity consumption of the dryer, using a real farm as a reference. The analysis has considered the use of the batteries, evaluating the level of energetic autonomy and the viability of the system, as well as future price scenarios. The second one has been about the solar electricity and its possible contributions to the heating needs of crop drying. In this case, rather than analysing the aspect of the energy numerically, it has discussed in a theoretical level about different possibilities.

First, it is important to mention that the availability of the data related to grain drying has been very limited. Besides the variations of the energy consumption in crop drying and the difficulties of theoretically defining standard values, there is very limited information about the energy that is actually used in farms to dry crops. The only data of the energy consumption in the Finnish level has been about the fuel consumption of three years, and no other source of information has been found to specify better the actual energy use. Little real measurement is done, in general, in the agricultural activity that constitutes one of the largest energy consumers in the sector. Therefore, tracking the energy consumption of crop dry, on a local level as well as on the general level, is essential for the development of this sector towards cleaner energy and food systems.

Another important thing to mention also is the energy efficiency. As in most of the cases, especially in the area of renewable energies, the energy efficiency is an important aspect to take into account when looking at the energy consumption and the different possibilities of covering them. Also in crop drying, significant savings can be achieved often by improving the technical efficiency of a system, or by just changing certain practices. However, this thesis has focused on the potential of the energy production in a theoretical level, and the efficiency aspect has not been considered. Always before looking at possibilities of energy production, attention should be put first to energy efficiency and possibilities of reducing energy needs.

In few words, the main conclusion of the thesis is that there is good potential of renewable energies for the Finnish agriculture, in this case potential of solar energy for the process of crop drying. A full level of energy autonomy is challenging to achieve with current conditions, but the use of fossil fuels could be dramatically decreased or even avoided, partially by the adoption of solar energy. As seen in Section 4.1, the same amount of electricity consumed in Finland in the drying process of crops could be produced with solar energy, by installing 120 m² of solar panels in every farm that produce crops. Considering usual sizes of farms in Finland, it could be said that most of them have such rooftop areas or even more suitable for PV. In the case of heating needs, if assuming that heating could be done directly with electricity, half of the rooftop area of rural residential buildings could produce energy as much as the average annual heat consumption for crop drying in Finland.

Further, the use of the heat pumps could decrease the needed surface three or even four times due to their capacity of transforming and increasing the electric energy into heat.

In the first case study, where solar energy has been addressed from the perspective of the electricity use in the dryers, one of the main conclusions has been the importance of considering other energy uses. That is, it has been seen that a PV system of 30 kWp would be economically viable even without the support for the investment, but for the case where the produced energy also is used for domestic and other energy consumptions. If only the consumption of the dryer is considered, the PV installation would be viable only with the support and without the storage. Hence, it is very important that when considering such systems of local energy production, it should be able to provide the energy for other possible uses, increasing the self-using rate.

When it comes to the energetic aspect, it is logical to think that a higher energy autonomy and a higher self-use rate improve the feasibility of the system. However, the results of the simulations have shown that dimensioning a PV system in order to have larger autonomy or self-using rates can decrease the economic viability of the system, at least with current conditions. One reason behind that is the high price of batteries in relation to their contribution in such energy-intensive activities. In that way, it has been seen that batteries are more preferable to use in energetically less intensive activities, and that adding more capacity can cause the installation to be economically negative even if the autonomy level increases.

Thus, achieving energy autonomy is challenging, especially only with solar energy and in such cases, where high consumptions occur in short periods and where the produced energy may not have other uses at other times. Nevertheless, the solar PV production can bring significant savings to the consumed energy as well as important economic savings. As stated in Section 4.2, the role of energy price is very important, and its increase would have a positive impact on the viability of this renewable energy production system. The decrease of the investment cost also would improve their viability, especially for the larger sizes of PV and battery systems. Indeed, the sensitivity of the PV and battery systems to price variations has been one of the main conclusions from the simulation, especially the sensitivity to price variations of energy.

Regarding the solar PV and the heating needs of crop drying, a brief comparison of both energies has shown the difference between the energy-intensive consumption and the low-density production. Naturally, the solar energy alone does not have sufficient capacity to cover the heating needs of crop drying, but it can be relevant in the electrification of the process. There, heat pumps could take an important role either becoming heat producers to dry crops or supporting the heating needs. In the latter case, using heat pumps could optimize the heat produced by the heaters and thus significantly reduce the fuel consumption. Bio-heaters already enable to produce the heat for crop drying by avoiding the use of fossil fuels, as seen in both reference cases in this thesis. In addition, heat pumps could optimize their heat production and minimize the emissions produced by burning fuels —wood chips in this case.

Furthermore, using industrial heat pumps directly to dry crops would dramatically decrease the fuel consumption in agriculture, and simultaneously lower energy costs of the drying through the electrification. Here, the solar energy could contribute by providing free energy, to a point where theoretically crops could be dryer with no extra cost besides the capital investment and basic maintenance. Therefore, the price development of PV systems and heat pumps, as well as the price development of the energy, play an important role in the future of agriculture and its environmental concern. Hence, further research is needed on heat pumps, and also other ways such as regulations and further support policies could create better conditions to adapt energy production systems based on cleaner sources.

As mentioned above, results in Section 4.2 demonstrate that the viability of the PV production system improve when other energy uses are included in the calculations. That means that the solar electricity would be used for other uses such as the domestic energy consumption when the dryer is not working. The more of other energy uses are covered with solar energy, the more increases its feasibility. Logically, that leads to think that other agricultural activities could fit well in such cases. That is, the potential and usability of solar energy could be increased by combining different production processes or energy consumptions in a way that more solar energy would be consumed locally and larger energy savings would be achieved. In that way, the electrification of agriculture would bring new possibilities of combining different energy uses, and would enable to optimize the use of solar electricity as well as other renewable energy sources. Electric agricultural machines, for instance, besides consuming the excess solar energy, could work as storage systems if the energy is not used by themselves. Such combinations could open up new possibilities of micro grids or smart grids in agriculture, and could gradually create better conditions for an energetically more autonomous sector, with better energy security and free of fossil fuels.

In addition to all of the mentioned above, is important to highlight the importance of other aspects that go beyond the technical or technological scope of the energy. Similarly to many other cases where energy or technologies are involved, other approaches that consider different aspects may contribute positively, or even completely change possible solutions to the situation. Different ownership structures of the energy production are a good example of that, as seen in the case of Kustavin Agri, one of the reference cases used in this thesis. There, instead of having five separate dryers, one is shared by five partners, thus costs are also shared among all partners. In the same way, a shared local energy production system would be more feasible, as the investment cost would also be distributed and its energy could be optimized with different users. Saying that, cannot be ignored the potential of the energy communities in the development of the use of renewable energies, as they offer an interesting approach to the clean and local energy production.

In the same line, aspects such as the use of time and the use of resources may need more attention. Especially in this situation where the energy system is getting obsolete and new sources of energy are needed, the temporal and physical use of resources is becoming more relevant. Section 4.2, for example, has shown temporal matters of the solar production and the energy consumption, where better results could possibly be achieved by shifting the consumption to sunny days instead of using batteries. The other reference case, in addition, is a good example of the use or resources in an efficient way by sharing, as only one heat production unit is used for the town needs as well as for the dryer. Thus, timing and sharing, for example, are approaches that enrich the matter of the energy in the current context, and simultaneously bring broader questions that may challenge the actual mindset about the energy needs and availabilities. That is, the paradigm of whether the available energy sources should fit to energy uses or whether the energy uses should fit to the available energy sources.

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